

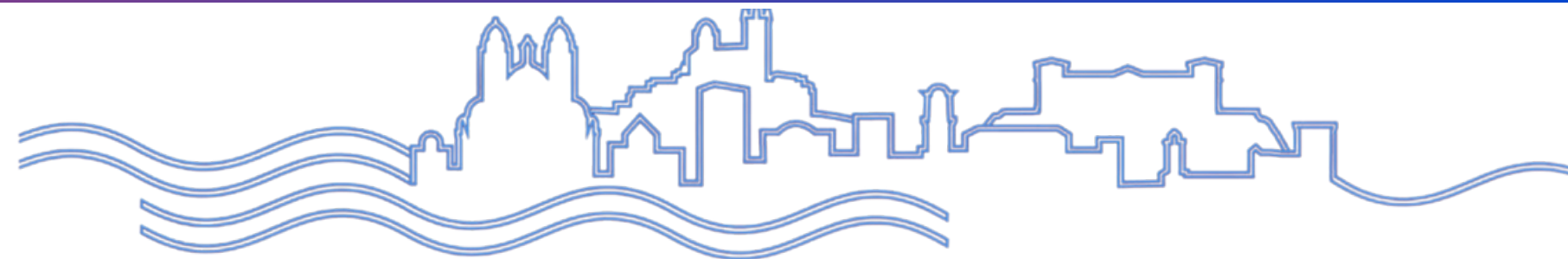
Muon Colliders and their Future R&D

EPS-HEP Marseilles
T13 Accelerators for HEP
Monday 7th July 2025

R. Taylor

D. Schulte, C. Rogers, F. Meloni

Featuring work from 450 members of the International Muon Collider Collaboration



Overview

WHY

should we collide muons?

HOW

would we collide muons?

WHAT

do we need to do to collide muons?

WHERE

might we collide muons?

WHO

works on colliding muons?

Overview

WHY

should we collide muons?

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would we collide muons?

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WHERE

might we collide muons?

WHO

works on colliding muons?

Physics!

Accelerator!

R&D!

Siting!

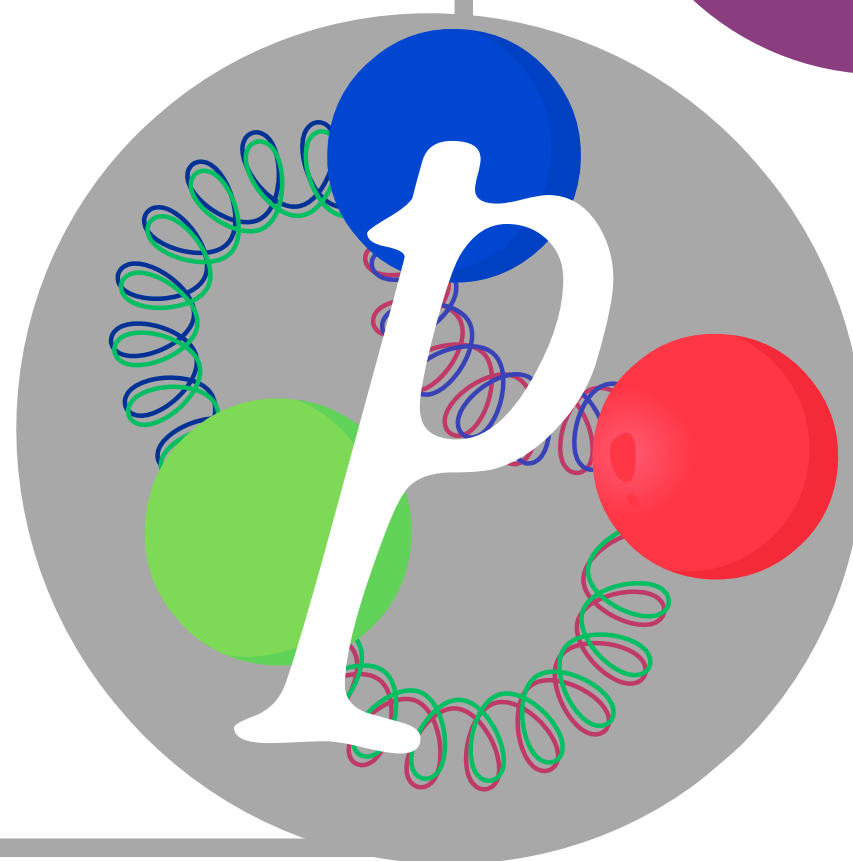
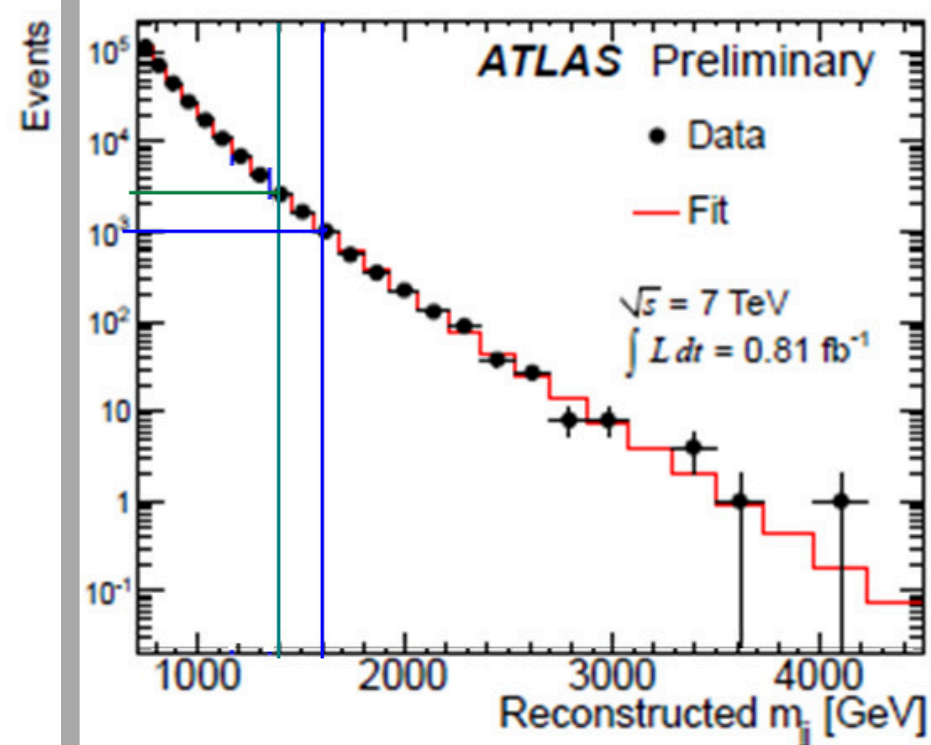
Collaborators!

WHY

should we collide muons?

Muons are:

- Fundamental particles
- Hadrons** collide with a fraction of their full energy



Muons are:

- 200x heavier than **electrons**
- Emit 6×10^{-10} less bremsstrahlung / turn
- $$\Delta E \propto \frac{E^4}{m^4 r}$$

Muon colliders are:

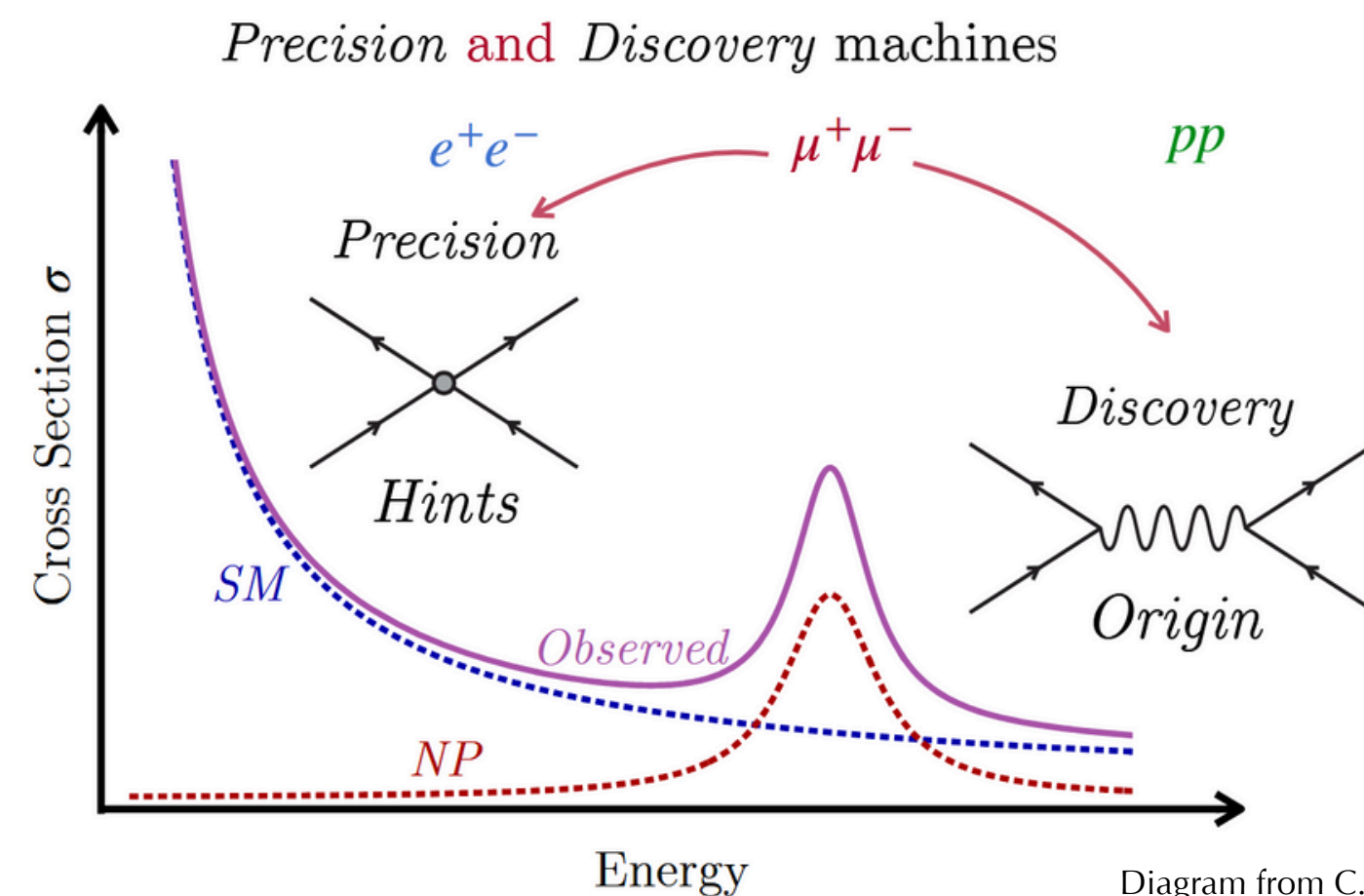
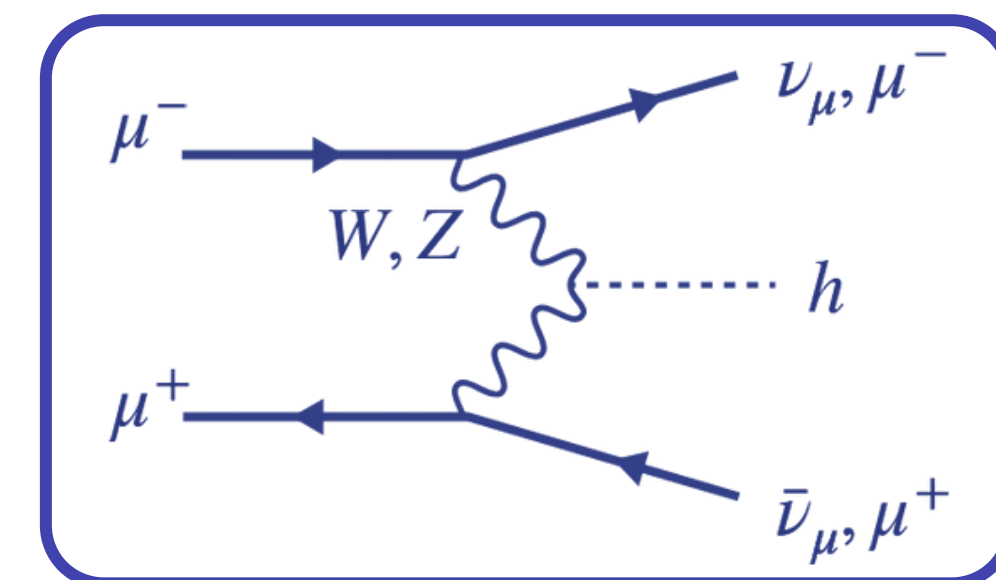
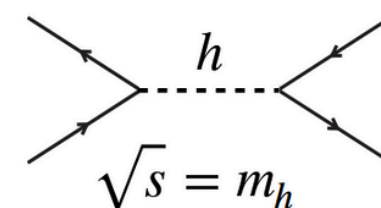


Diagram from C. Cesarotti

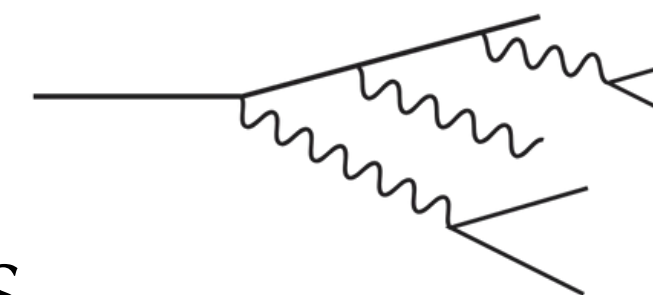
WHY

should we collide muons?

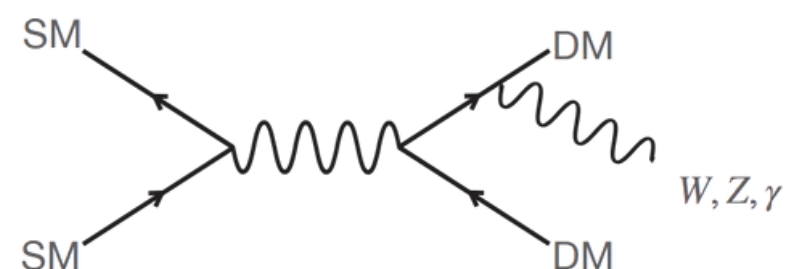
Muons at high energies are **vector boson fusion (VBF)** factories. S-channel directly has lower cross-sections.



At high energies, muons radiate gauge bosons like photons.



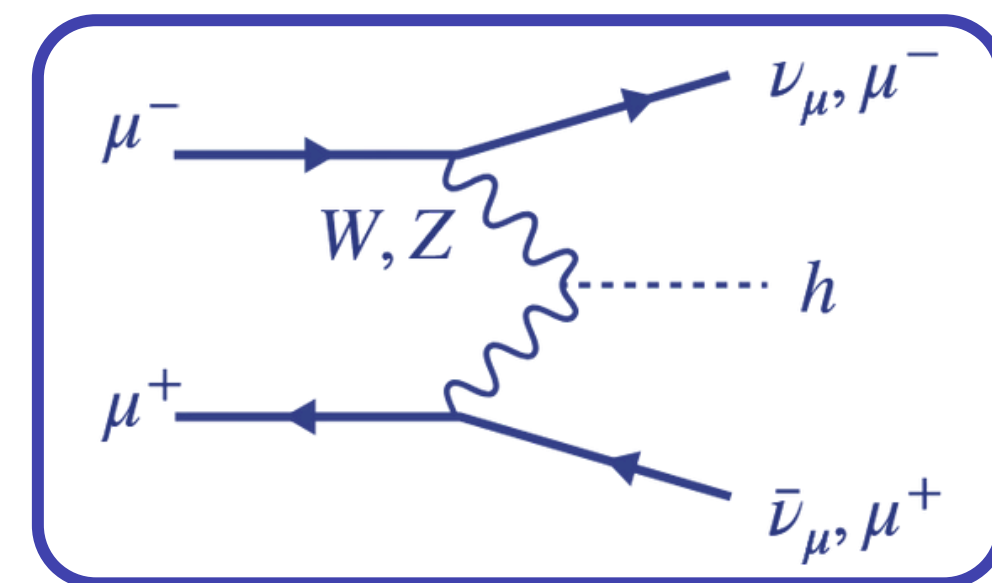
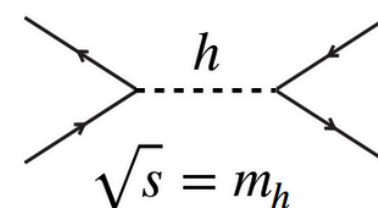
Ideal environment for **electroweak** studies, including WIMPS.



WHY

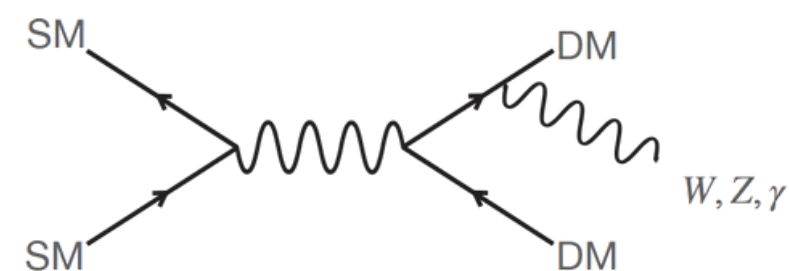
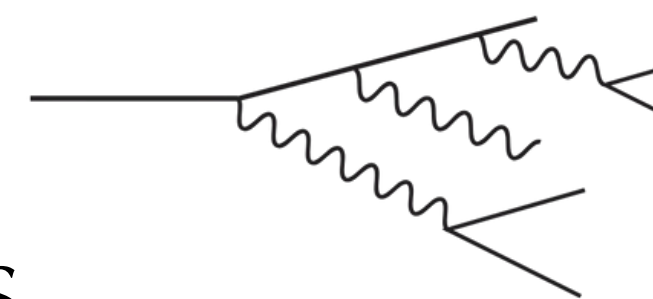
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Ideal environment for **electroweak** studies, including WIMPS.



IMCC and MuCol
Following ESPPU 2022

2023 --->

Muon Ionization Cooling Experiment (MICE)

UK-based cooling experiment

2004 - 2019

Muon Acceleration Programme (MAP)

Fermilab based programme

2011 - 2017

The Neutrino Factory and Muon Collider Collaboration (NFMCC)

Produced a NuFact design at CERN

1999 - 2011

Muon Collider Workshops

Annual workshops, mostly in the US

~1992 - 1999

First published muon collider concepts

G.I. Budker & A.N. Skirsky
at Novosibirsk

~1969

Shoot For The Muon!



HOW

would we collide muons?

Challenge 1:
Need to produce the muons

Challenge 2:
The muons decay

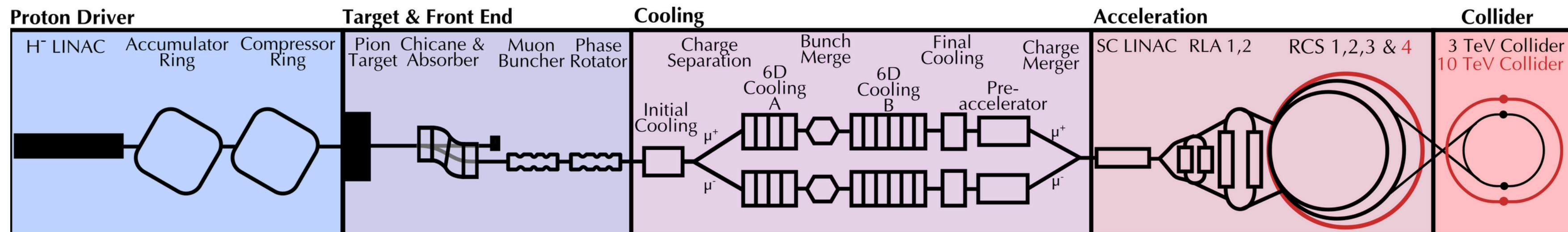
Produce a
high power
proton beam

Target material
to withstand
high-power

Rapidly reduce the
beam size

Rapidly
Accelerate

Collide
tight
beams



R. Taylor v1.5 (2025)

Challenge 3:
Need to adjust for collective effects due to
high intensity beam across the complex.

HOW

would we collide muons?

Energy!

Either

3 TeV

or

10 TeV

Center-of-mass

Luminosity! 2×10^{34}

or

 20×10^{34} for 16 T $\text{cm}^{-2}\text{s}^{-1}$ luminosity 15×10^{34} for 11 T**Muons!** 2.2×10^{12}

or

 1.8×10^{12}

Luminosity also depends on:

- Transverse Emittance - 25 μm
- Longitudinal Emittance - 0.025 eVs

- Beta at IP: 1.5 mm
- Repetition rate: 5 Hz

$$\mathcal{L} = \frac{\gamma^3 \tau_0 c}{2C} \frac{N_0^2 \sigma_\delta}{4\pi \epsilon_{\perp, N} \epsilon_{L, N}} f_r$$

HOW

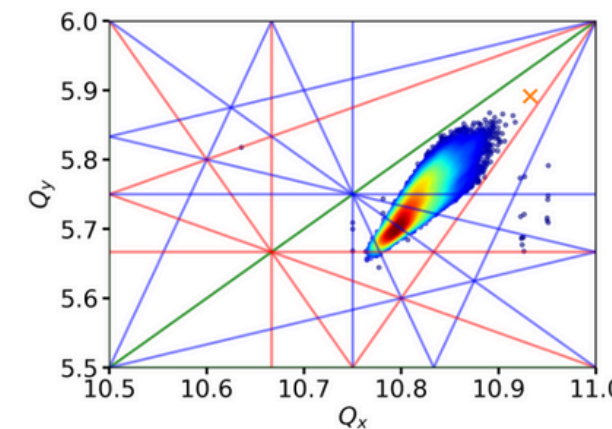
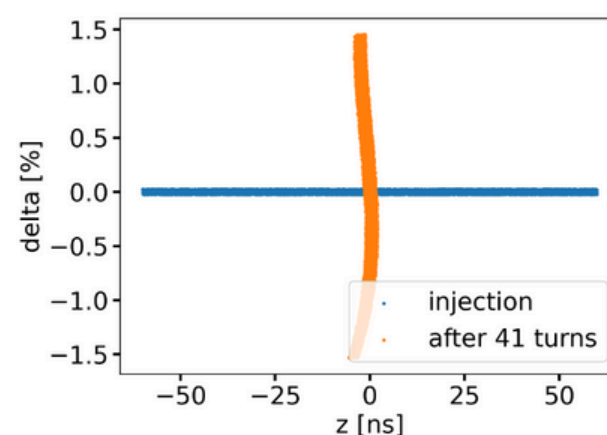
would we produce muons?

Challenges:

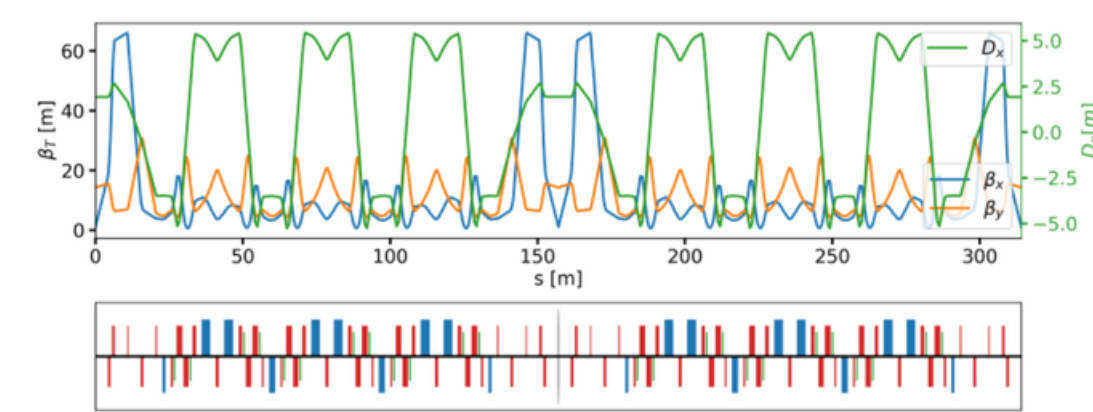
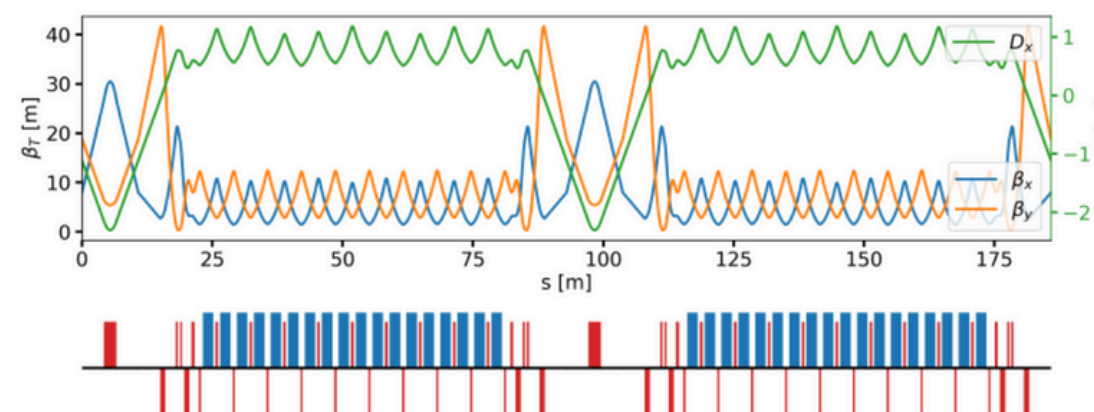
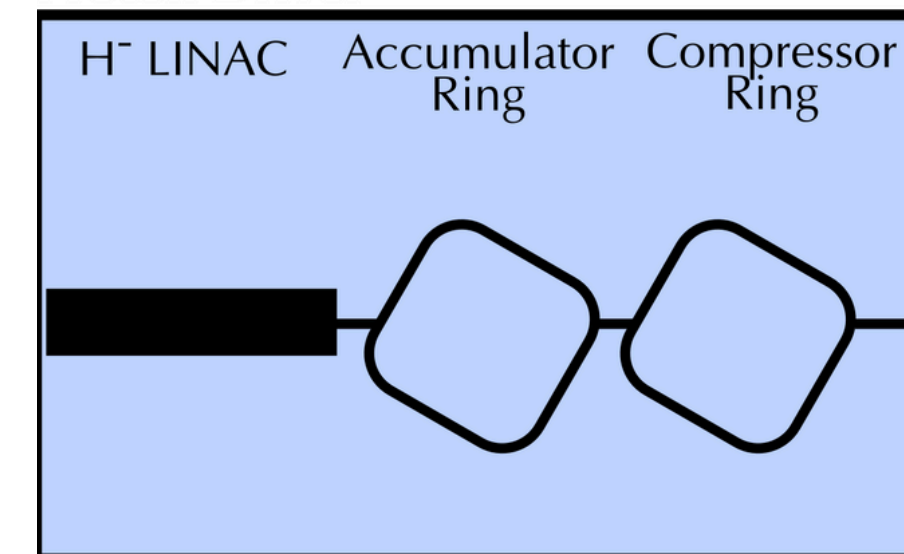
- High intensity proton beam
- 2 MW, 5 GeV or 4 MW, 10 GeV
- Accumulate 5×10^{14} p⁺/pulse
- Compress to 2 ns

Achievements:

- Lattice designs for accumulator and compressor rings
- Collective effects studies



Proton Driver



Future R&D:

- In parallel with other **high-intensity p⁺** facilities (SNS, ESS, CERN, JPARC, ISIS)
- High intensity, large-aperture **H⁻ sources** and **laser-assisted charge exchange** injection
- High transmission, high current RFQs
- Limitation of high intensity compression schemes with high space-charge

HOW

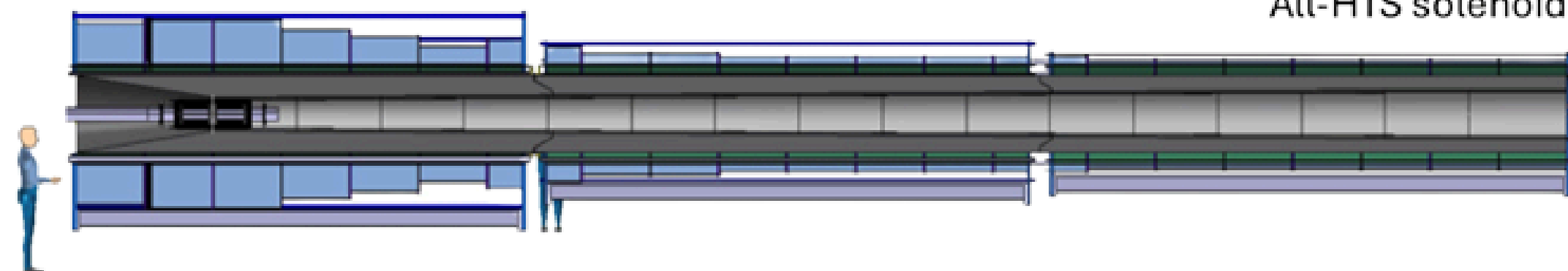
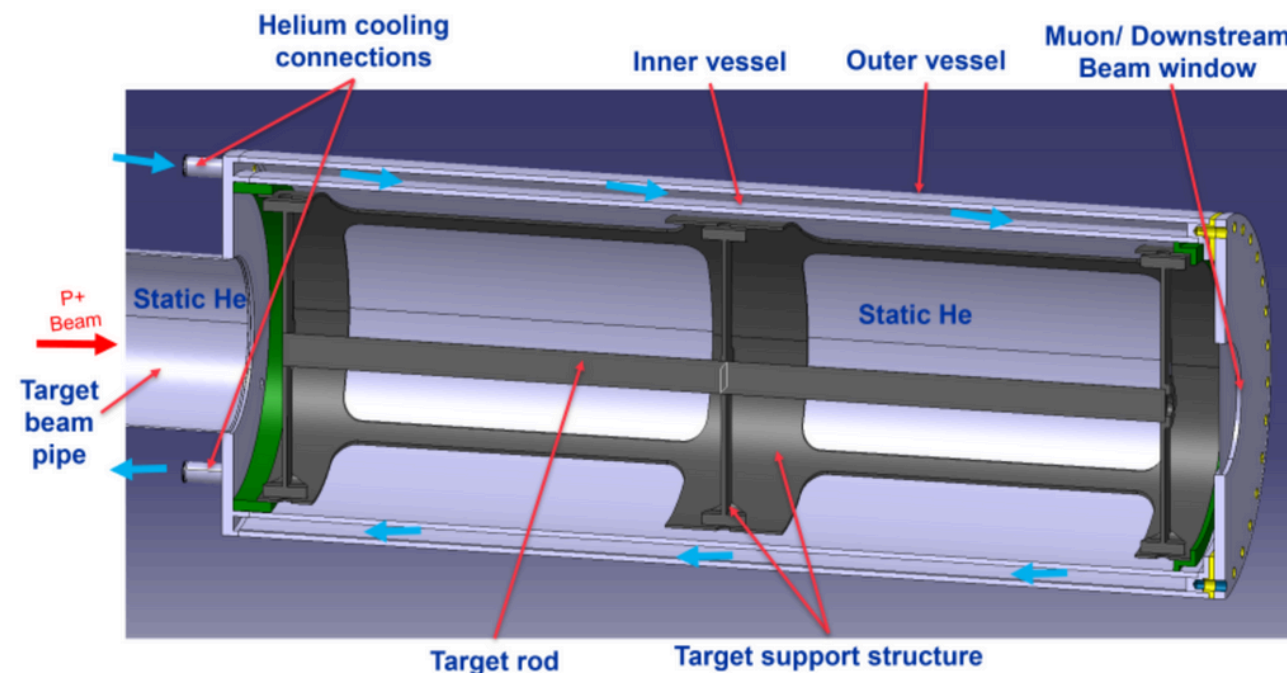
would we produce muons?

Challenges:

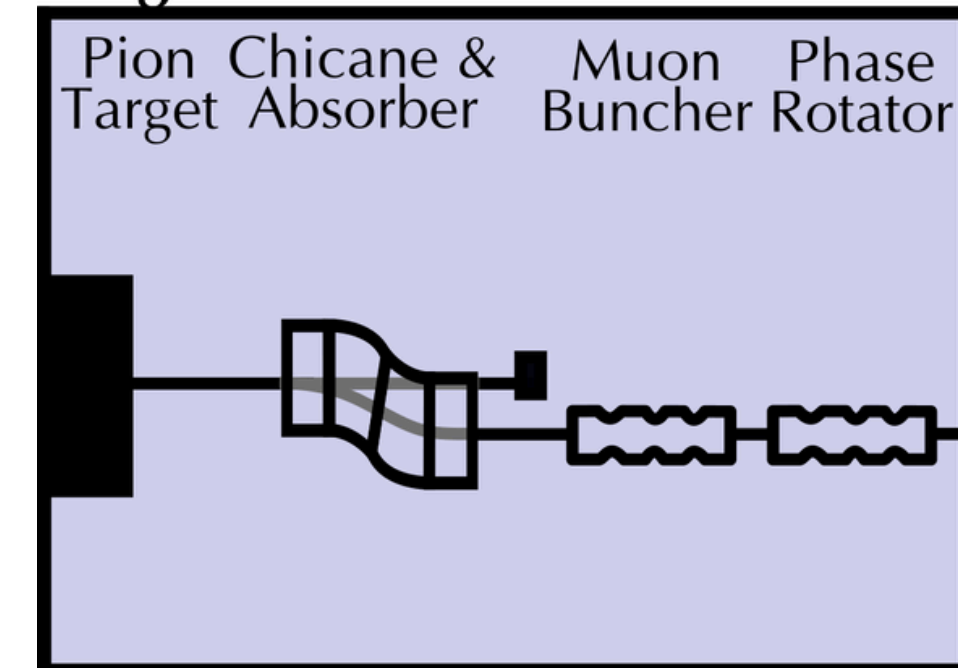
- 2 MW, 400 MJ/pulse on target
- Optimising for pion yield
- HTS solenoid capture system
- Extraction of spent proton beam

Achievements:

- Radial build of graphite target
- Studied radiation load on HTS
- Begin 4 MW targets, e.g. liquid Pb, fluidized W



Target & Front End



Future R&D:

- 1400 mm, 20 K, 20 T HTS solenoids with 80 MGy radiation. Synergies with fusion magnets.
- 20 MV/m RF cavities within 3 T, over large range of frequencies.
- Beam loading and collective effects in Front-End.

HOW

would we cool muons?

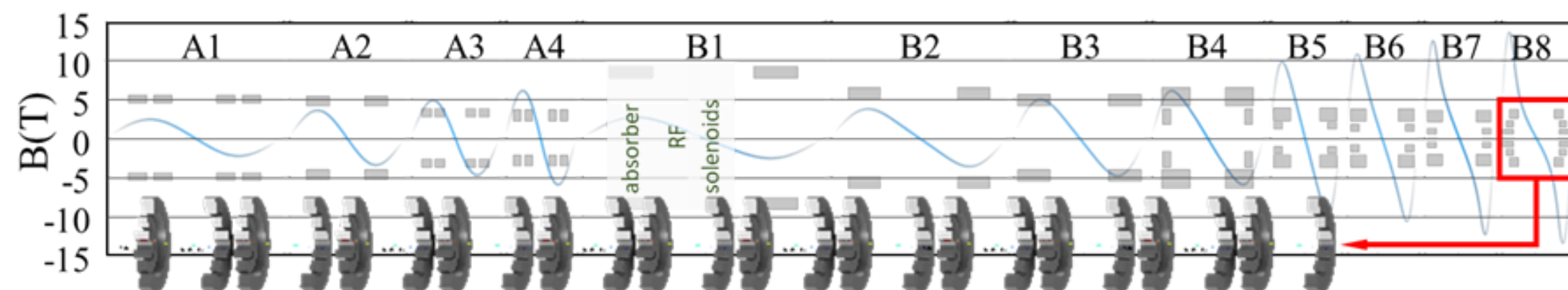
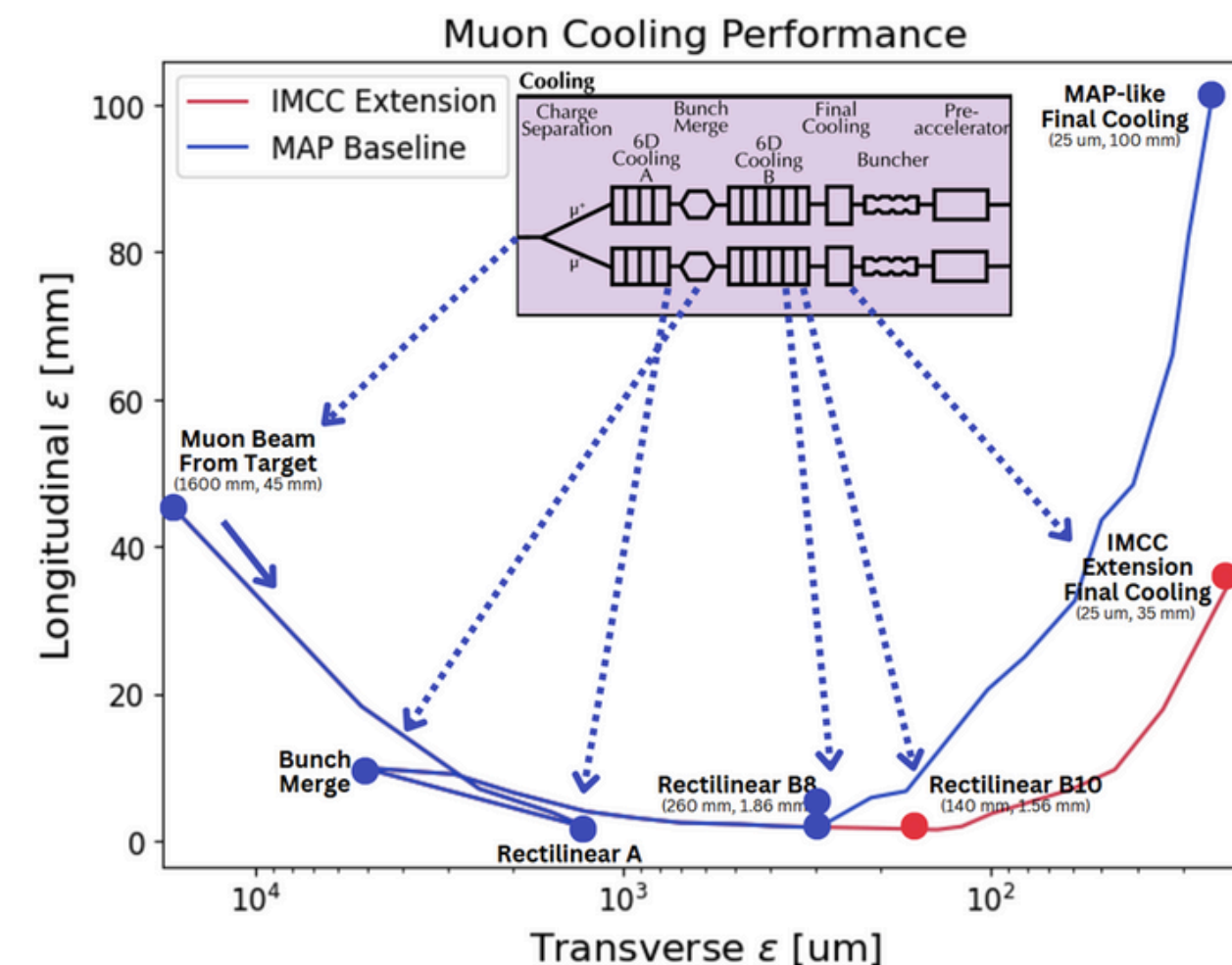
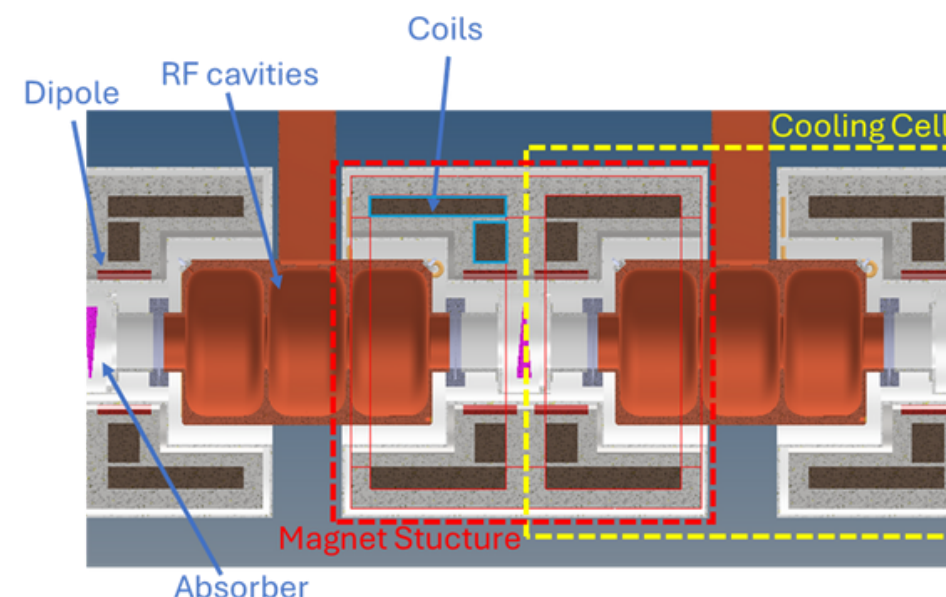
Reduce beam area in (x,px,y,py,z,pz)

Challenges:

- Overlapping dipoles, absorbers and RF cavities within solenoids.
- Bright beam on liquid hydrogen
- Beam loading and space charge

Achievements:

- Benchmarked codes, RF Track, BDSIM, G4Beamline, ICOOL
- Improved 6D cooling design



6D Future R&D:

- 2.6 - 17.9 T solenoids with 800 - 60 mm bore.
- >30 MV/m in fields >10 T.
- Develop **cooling demonstrator** to verify integration.

Final Cooling Future R&D:

- 40 T, 50 mm solenoids for final cooling.
- ~20 MV/m in 4 T fields from 200 - 5 MHz
- LH₂ pressure and windows

HOW

would we **accelerate** muons? Rapid-Cycling Synchrotrons (RCS)

Challenges:

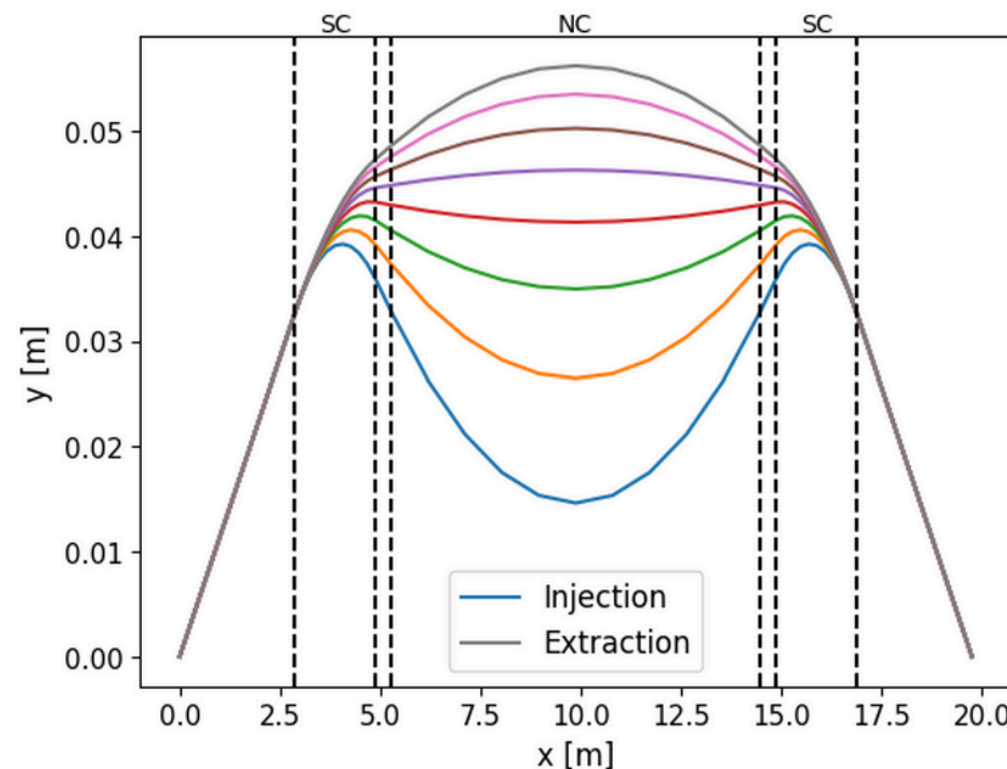
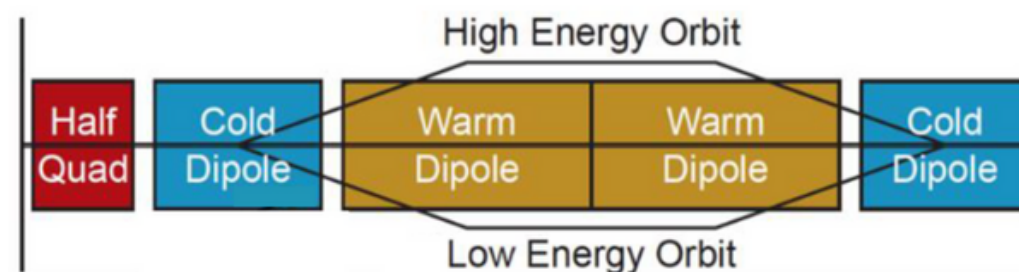
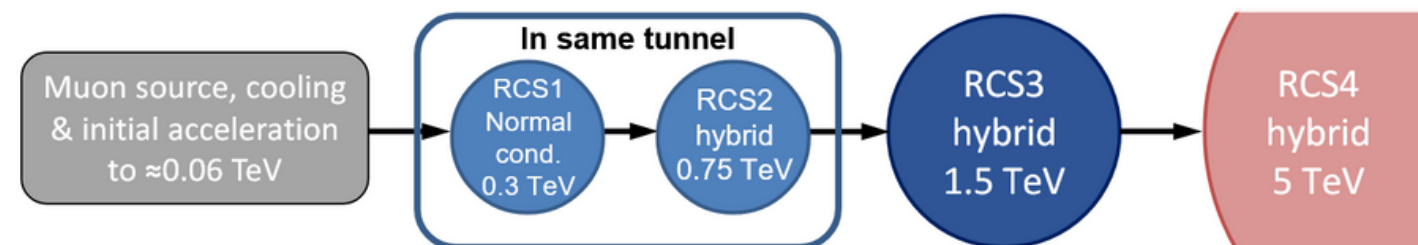
- Fast-Ramping NC magnets hybrid with static SC magnets
- Multiple RF stations throughout
- Large aperture from orbit

Achievements:

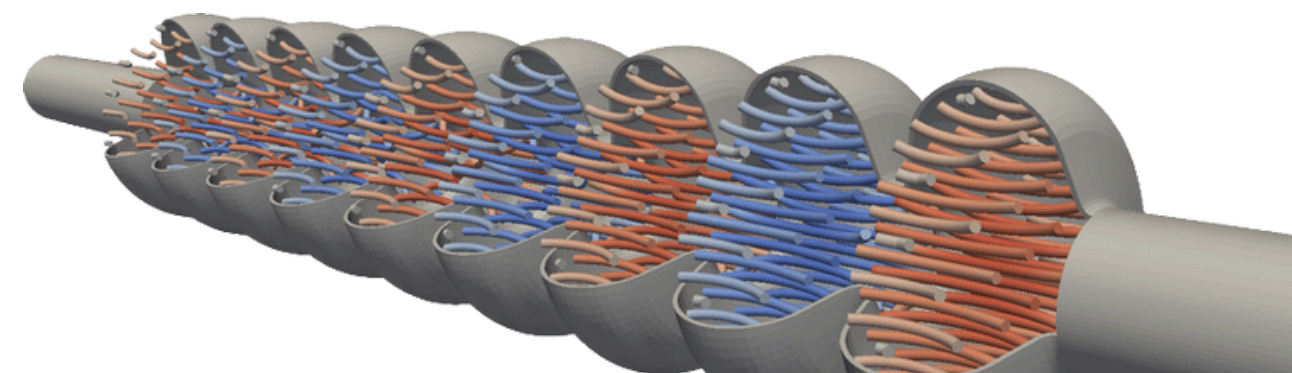
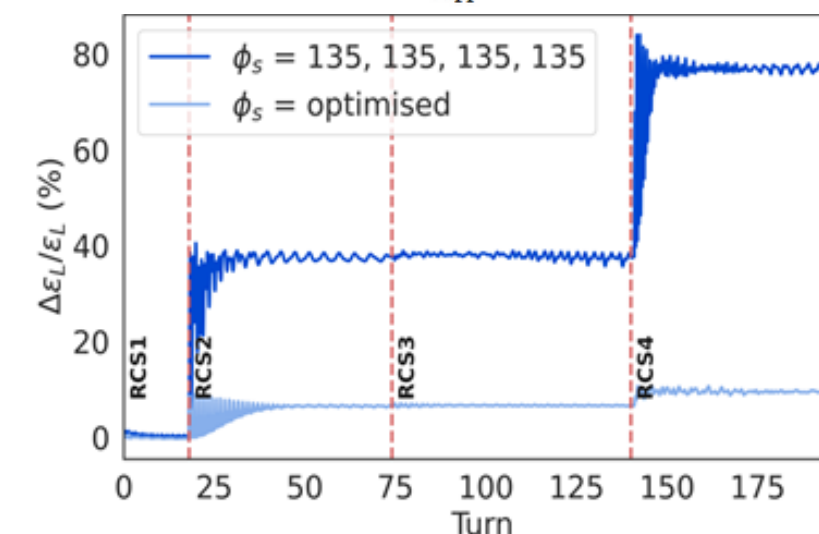
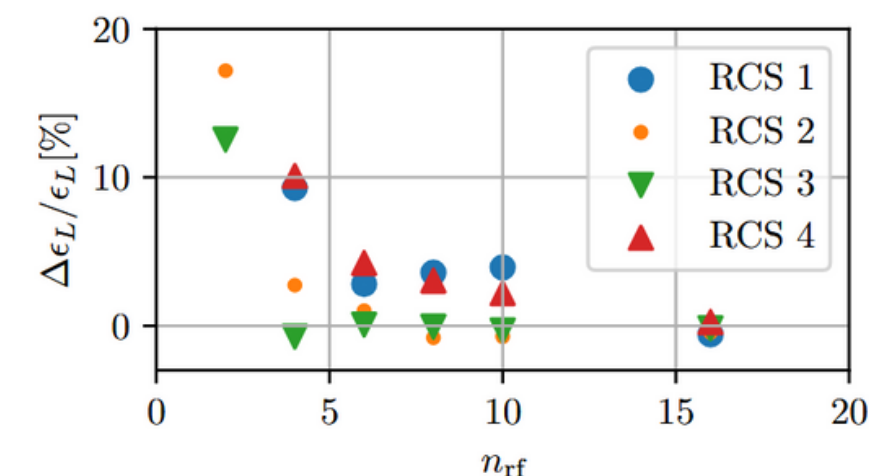
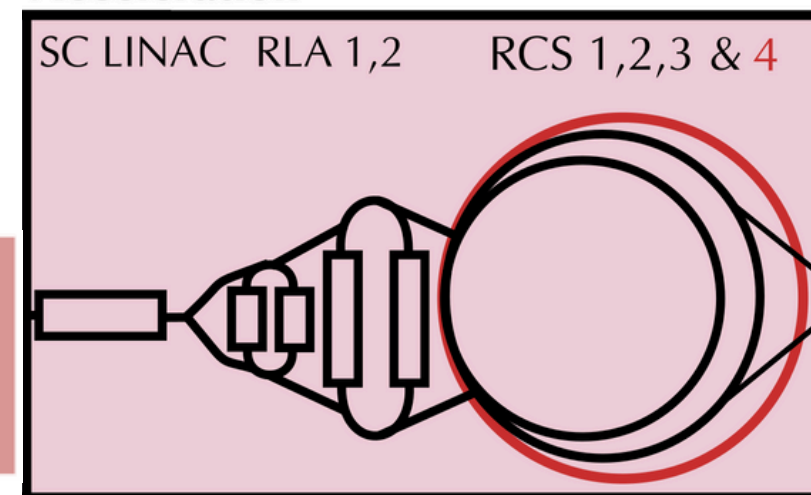
- Lattice designs & matching for greenfield and CERN RCS
- 1.3 GHz Tesla Cavities
- Impedance studies of RCSs

Future R&D:

- Designs of SC LINAC and Recirculating LINACS
- Validate power sources for 1.3 GHz
- Higher order mode damping schemes



Acceleration



HOW

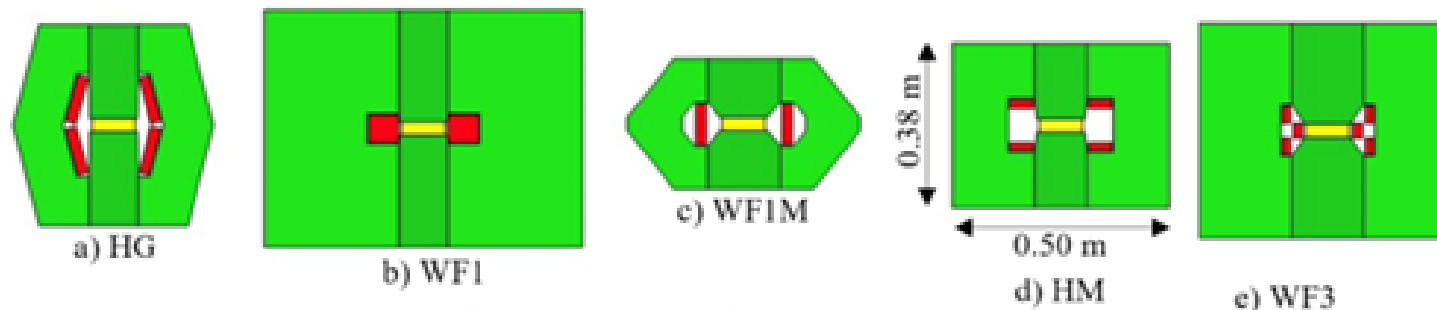
would we accelerate muons?

Challenges:

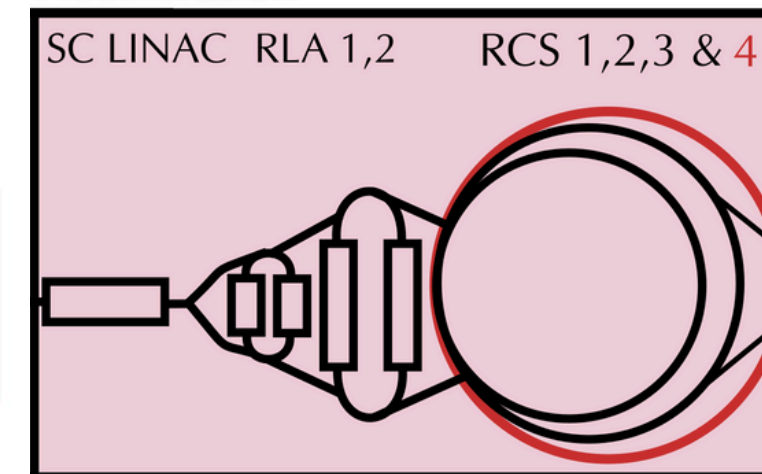
- 1-10 ms ramping NC magnets with 98-99% energy recovery of 200 MJ stored in magnets

Achievements:

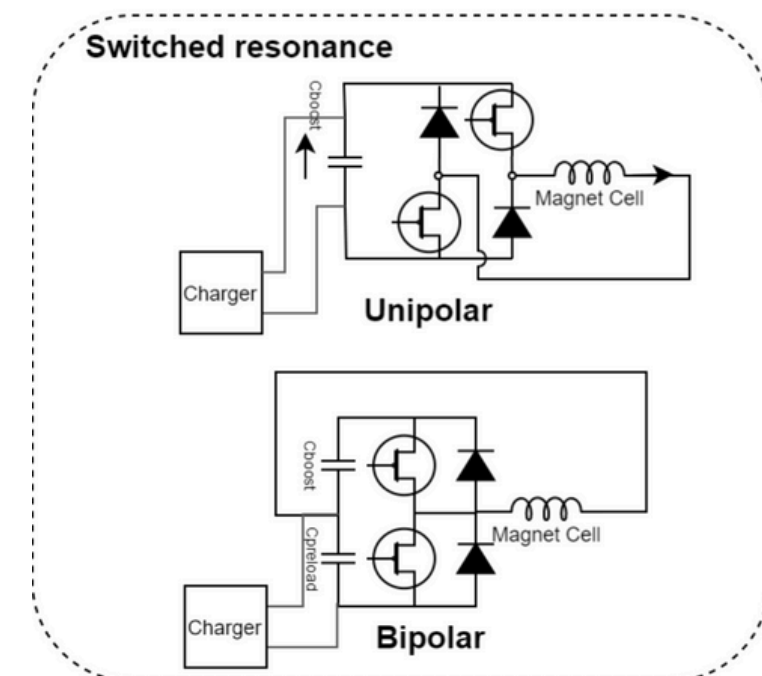
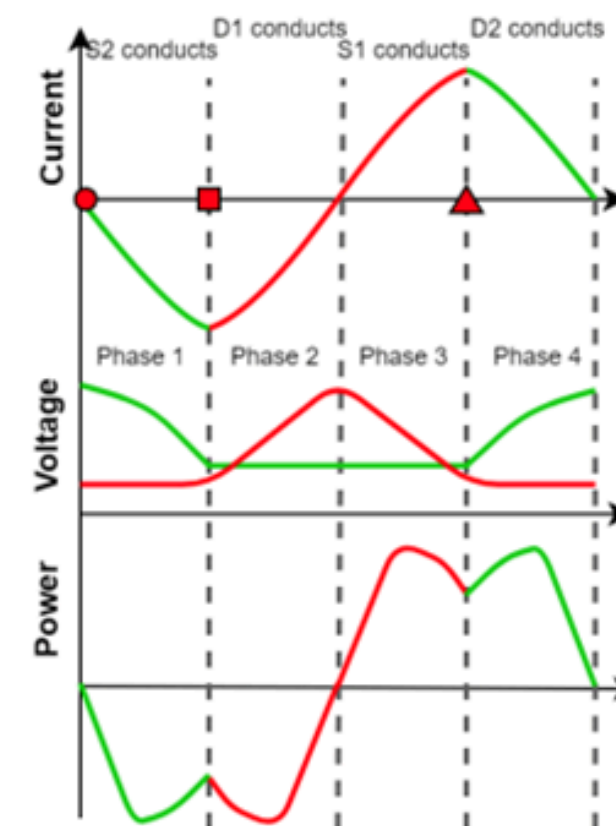
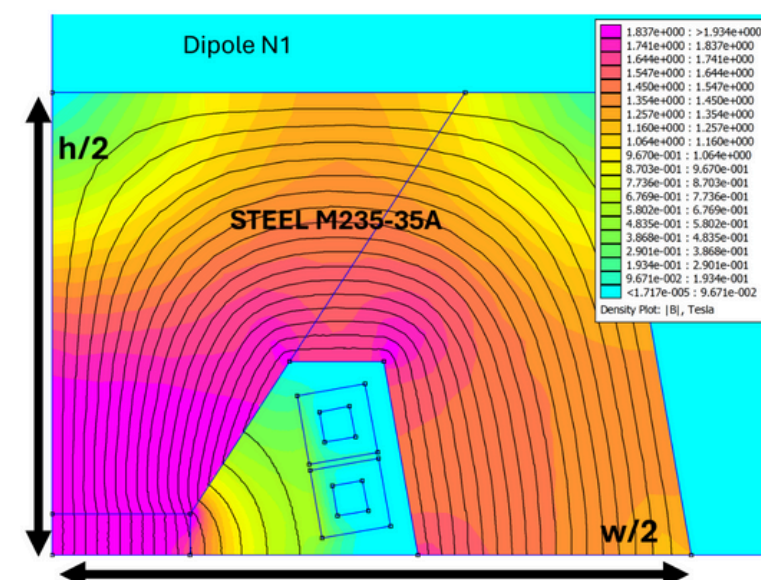
- Design of magnets, power converters, optimised together with RF
- Power converters switching magnet sign magnets without changing voltage direction



Acceleration



RCS	E [J/m]	E_iron [J/m]	E_copper [J/m]	Loss [%]	P [MW]
SPS 1	5447	10	52	1.1	1.9
LHC 1	5678	9.2	80.6	1.6	12.8
LHC 2	5752	63.4	298	6.3/2	26.6



Future R&D:

- 4 kT/s ramp rate
- Synergies with infineon for sustainable energy sources

HOW

would we collide muons?

Challenges:

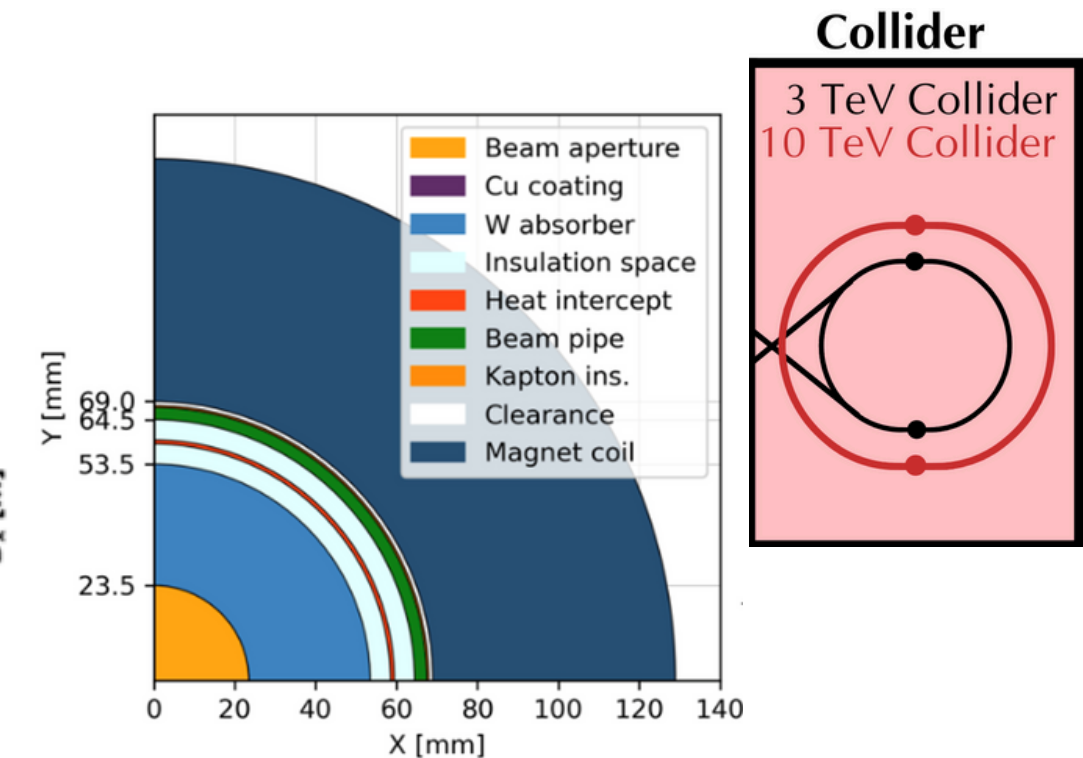
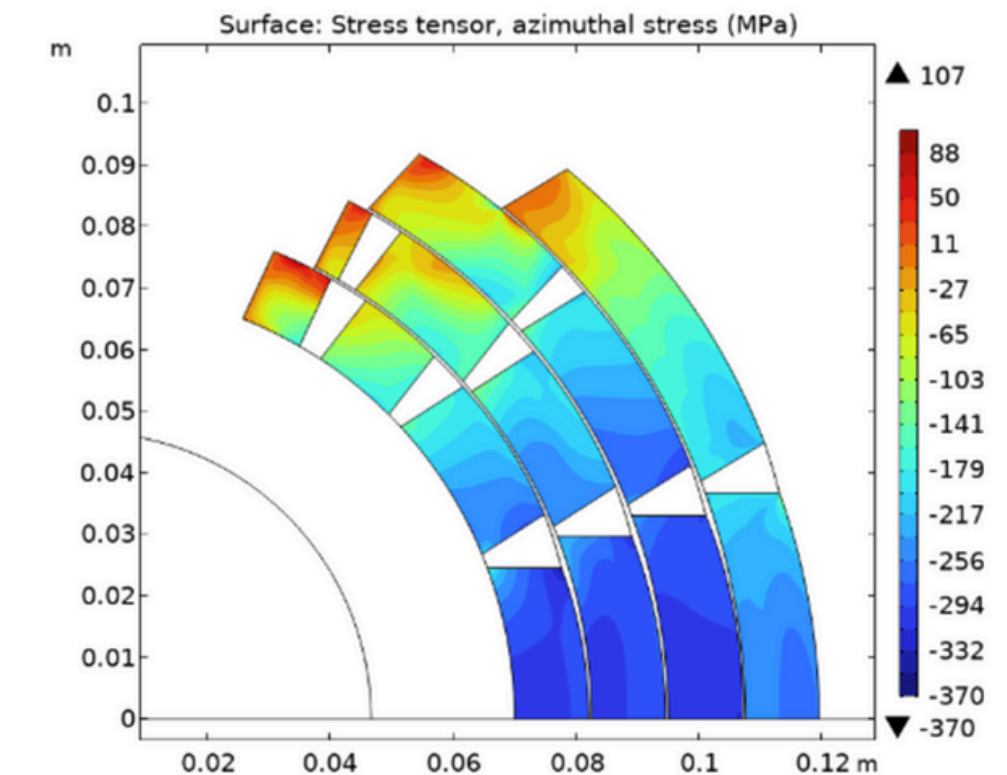
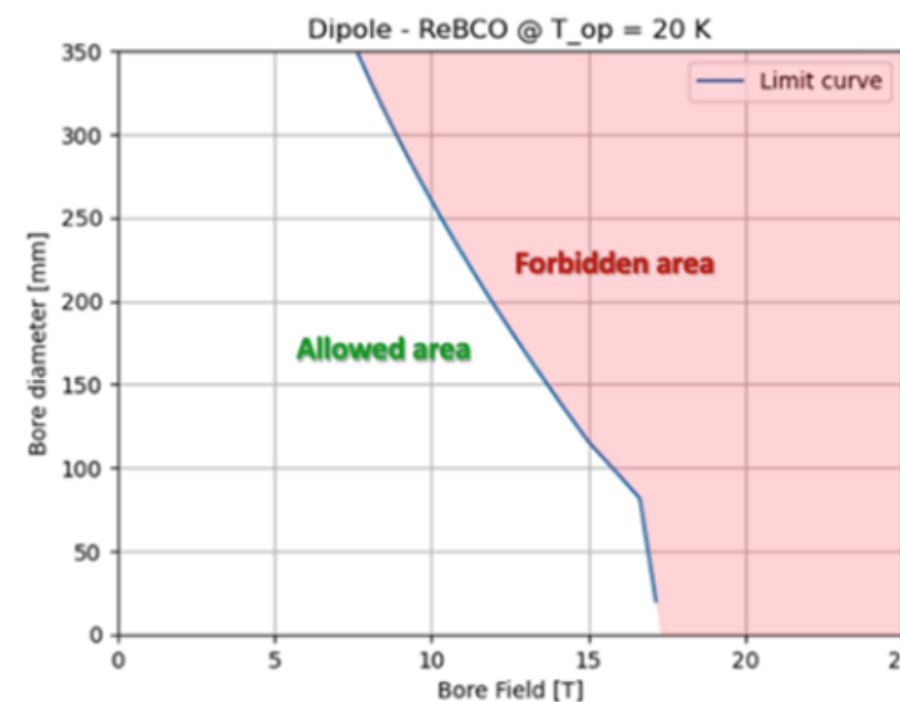
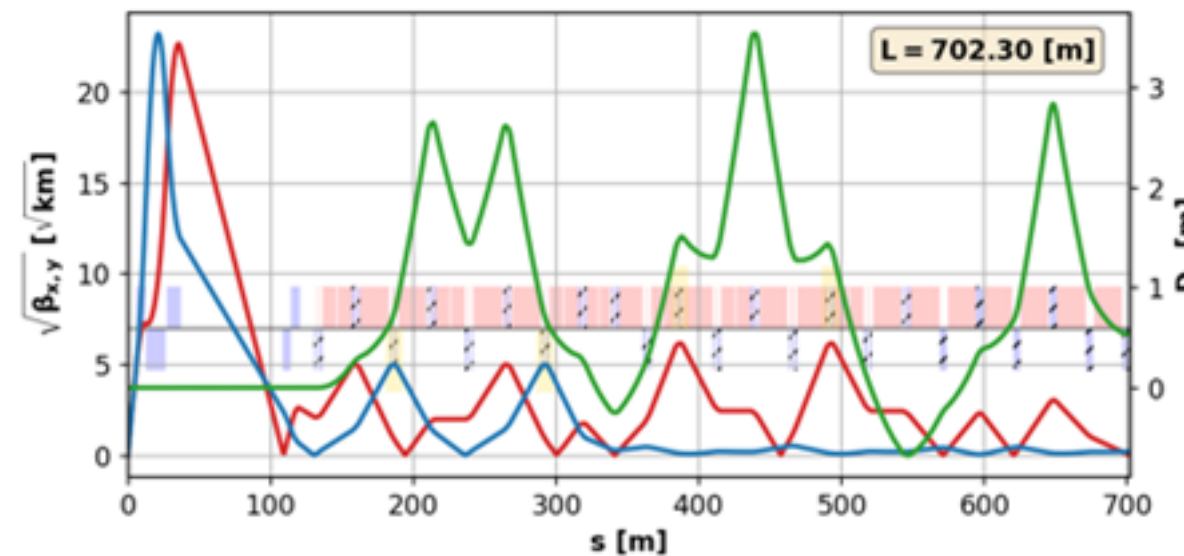
- Lattice design with β^* 1.5 – 5 mm
- 0.1% beam energy spread
- High radiation, 500 W/m loss
- High magnetic field / aperture

Achievements:

- Magnetic shielding design
- Cryogenic concept
- Impedance models

Future R&D:

- Studies on machine imperfections and misalignment
- Improve energy acceptance compensating chromatic effects
- *NbTi*: 4.8 T, 16 cm / *Nb3Sn*: 11 T, 16 cm / *HTS*: 14 T, 14 cm



Experimental programme is now essential

HOW

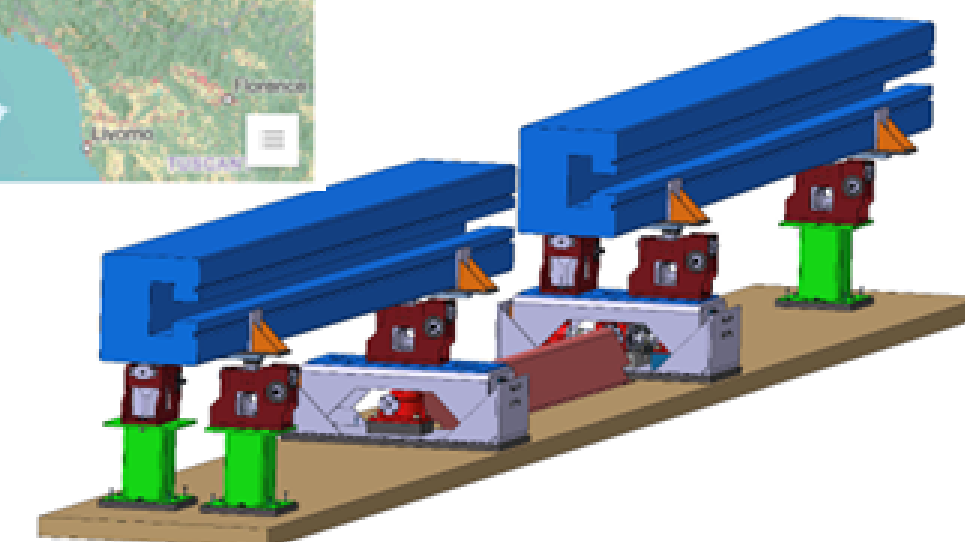
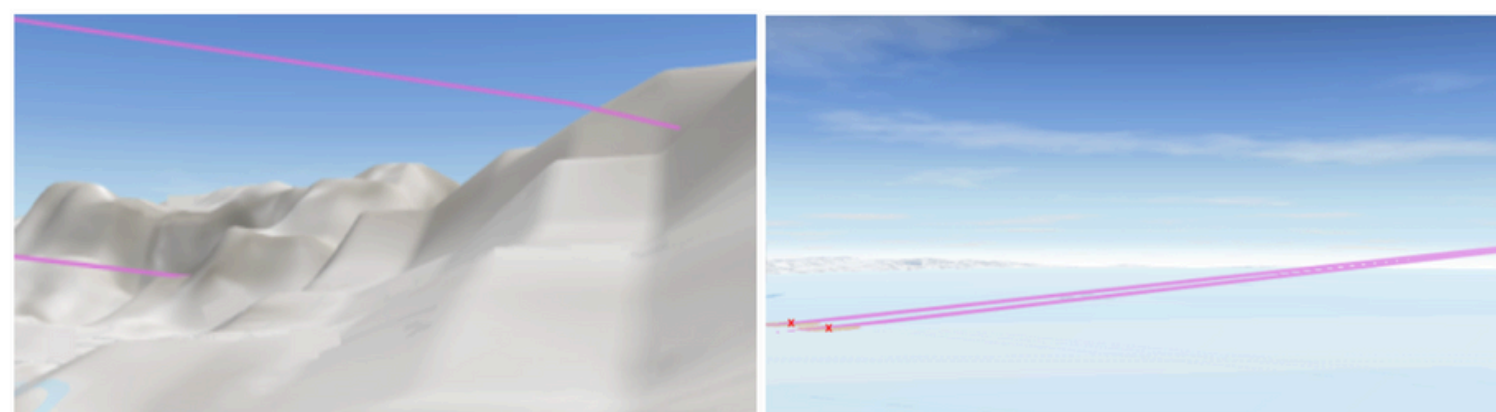
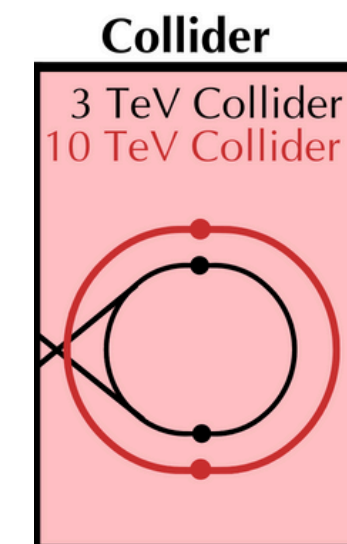
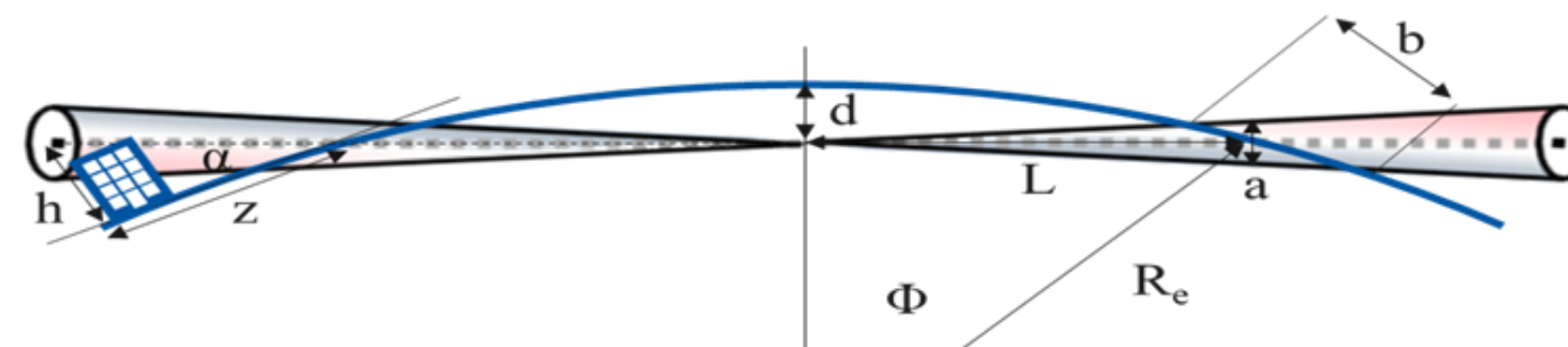
would we collide muons?

Challenges:

- Negligible neutrino flux
- Orient collider to benefit neutrino detector studies

Achievements:

- Geoprofiler for detailed modelling
- Orientation options found
- Conceptualised mover system



Future R&D:

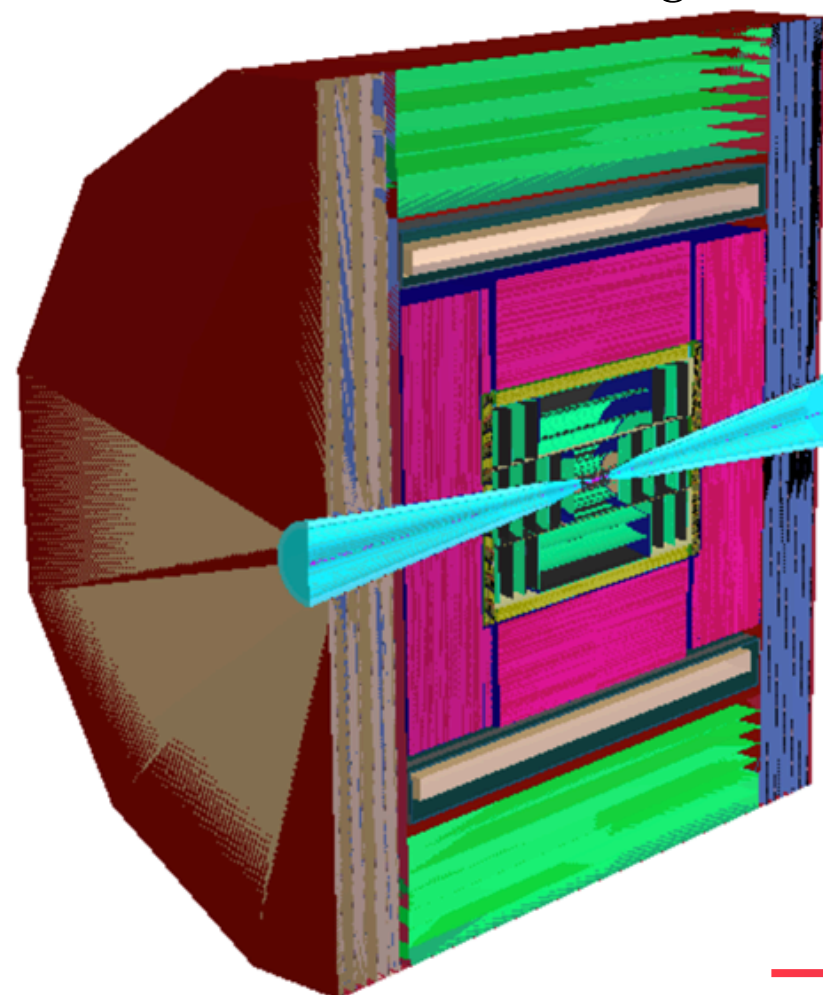
- Jack development programme to reach 1 mrad with 0.004 mrad tolerance
- Further iteration with collider lattice

HOW

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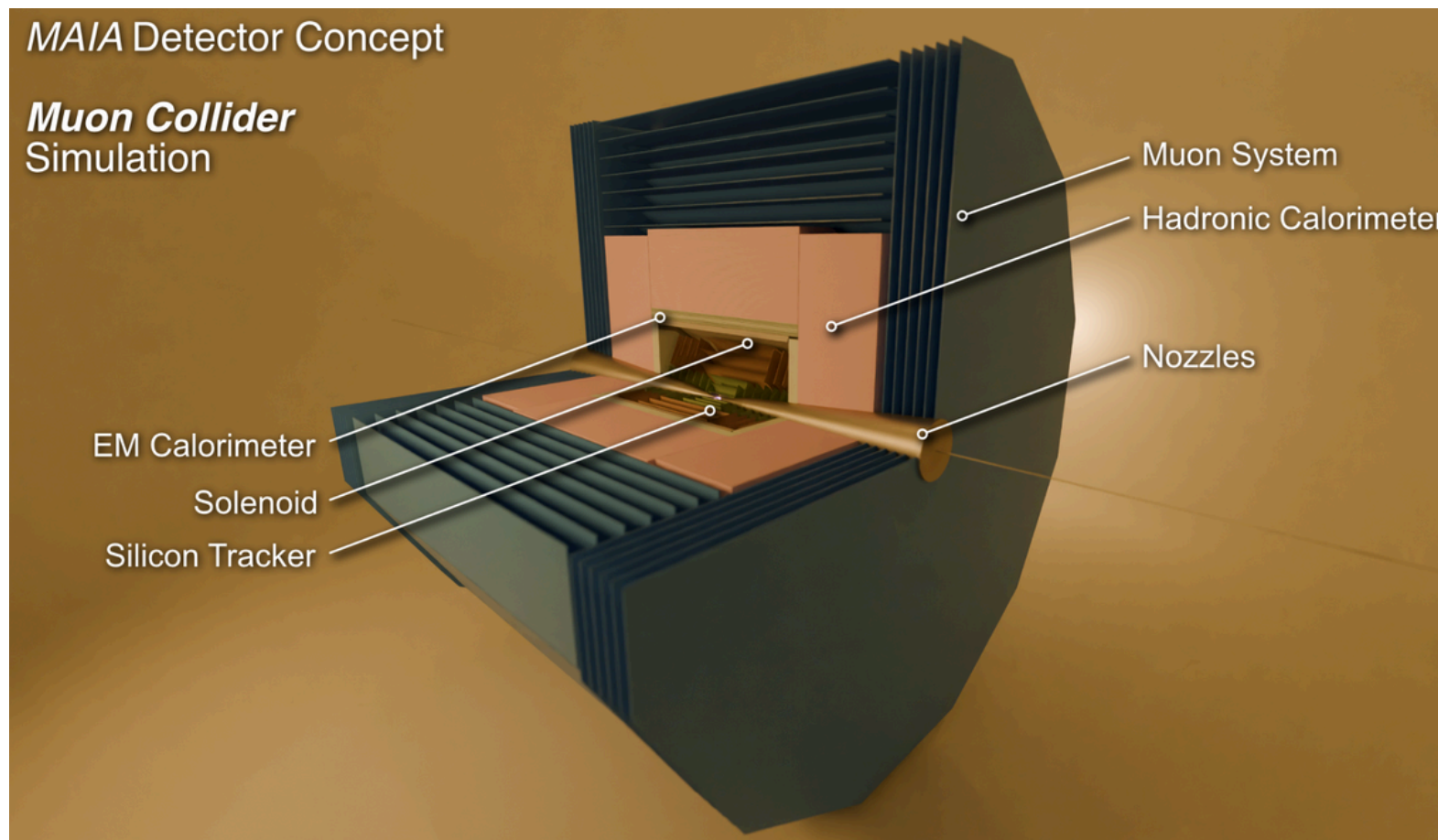
MUSIC

Muon Smasher for Interesting Collisions

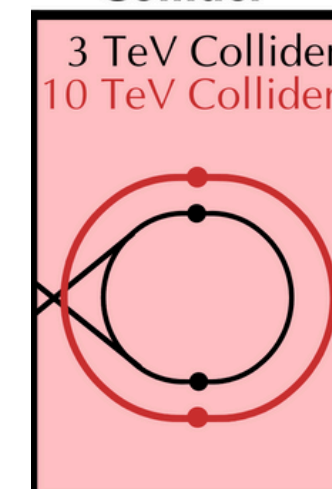


MAIA

Muon Accelerator Instrumented Apparatus

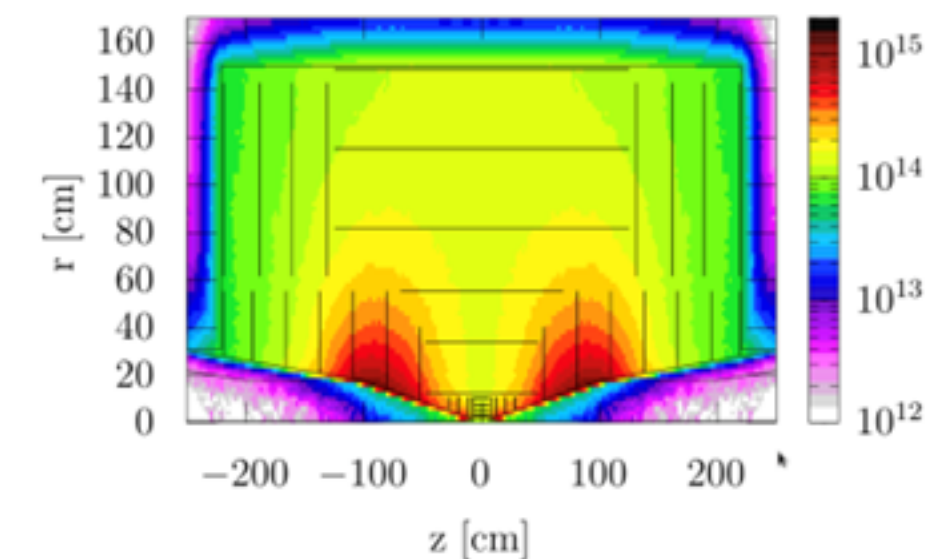
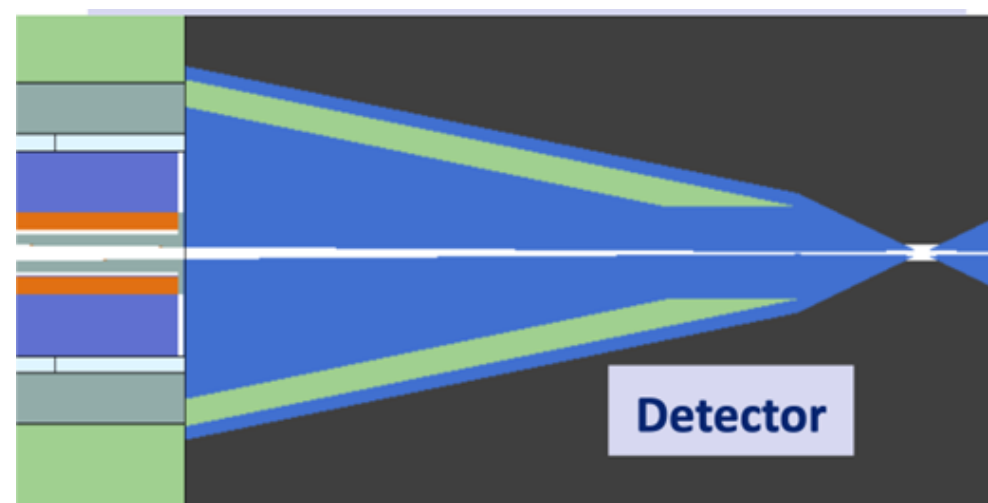


Collider



Future R&D:

- Reconstructing events with high BIB
- Tungsten nozzle configuration
- State-of-the-art detector technologies



WHAT

do we need to do to collide muons? Future R&D

Technologies	Deliverables	Key parameters and goals	Radiofrequency		
Magnets					
Target solenoid	Develop conductor, winding and magnet technology	1 m inner / 2.3 m outer diameters, 1.4 m length, 20 T at 20 K	Muon cooling RF cavities	Design, build and test RF cavities	352 MHz and 704 MHz in 10 T field
Split 6D cooling solenoid	Demonstration of solenoid with cell integration	510 mm bore, gap 200 mm, 7 T at 20 K	Klystron prototype	Design/build with Industry 704 MHz (and later 352 MHz) klystron	20 MW peak power, 704 MHz / 352 MHz
Final cooling solenoid	Build and test HTS prototype	50 mm bore, 15 cm length, 40 T at 4 K	RF test stands	Assess cavity breakdown rate in magnetic field	20-32 MV/m, 704 MHz–3 GHz cavities in 7–10 T
Fast-ramping magnet system	Prototype magnet string and power converter	30 mm x 100 mm, 1.8 T, 3.3 T/s	SCRF cavities	Design SRF cavities, FPC and HOM couplers, fast tuners, cryomodules	352 MHz, 1056 MHz, 1.3 GHz, 1 MW peak power (FPC)
LTS collider dipole	Demonstrate Nb ₃ Sn collider dipole	160 mm diameter, 11 T, 4.5 K, 5 m long	Muon Cooling		
HTS RCS dipole	Demonstrate RCS HTS dipole	30 mm x 100 mm, 10 T, 20 K, 1 m long	First 6D cooling cell	Build and test first cooling cell	
HTS collider dipole	Demonstrate HTS collider dipole	140 mm diameter, 14 T, 20 K, 1 m long	5-cell module	Build and test first 5-cell cooling module	
HTS collider quadrupole	Demonstrate HTS IR quadrupole	140 mm diameter, 300T/m, 4.5K, 1m long	Cooling demonstrator	Design and build cooling demonstrator facility	Infrastructure to test cooling modules with muon beam
			Final cooling absorber	Experimental determination of final cooling absorber limit	3×10^{12} muons, 22.5 μ m emittance, 40 T field
Design & Other Technologies					
Neutrino flux mover system	Protoype components and tests as needed	Range to reach O(\pm 1mradian)			
Beam Instrumentation	Instrumentation component designs	Protoype components and tests as needed			
Target Studies	Target design and test of relevant components	0.4 MJ/pulse, 5 Hz			
Start-to-End Facility Design	A start-to-end model of the machine consistent with realistic performance specifications	Lattice designs of all beamlines, simulation codes with relevant beam physics, tuning and feedback procedures			

WHAT

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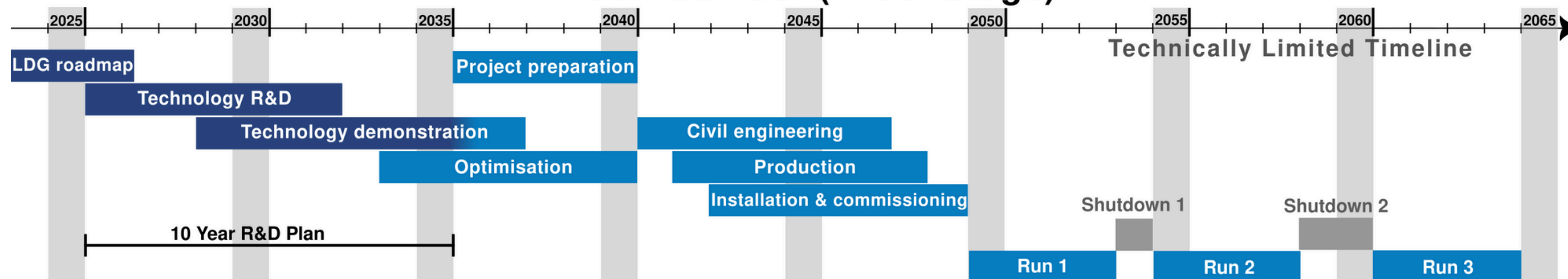
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Split 6D cooling solenoid	Demonstration of sole integration	<div>Totals: Duration 10 years Accelerator: 300 MCHF material, 1800 FTEy Detector: 20 MCHF material, 900 FTEy</div>			
Final cooling solenoid	Build and test HTS pr				
Fast-ramping magnet system	Prototype magnet stri converter				
LTS collider dipole	Demonstrate Nb ₃ Sn d				
HTS RCS dipole	Demonstrate RCS HT				
HTS collider dipole	Demonstrate HTS col	Infrastructure to test cooling modules with muon beam 3 × 10 ¹² muons, 22.5 μm emittance, 40 T field			
HTS collider quadrupole	Demonstrate HTS IR				
Neutrino flux mover system	Prototype components and tests as needed	Range to reach O(±1mradian)			
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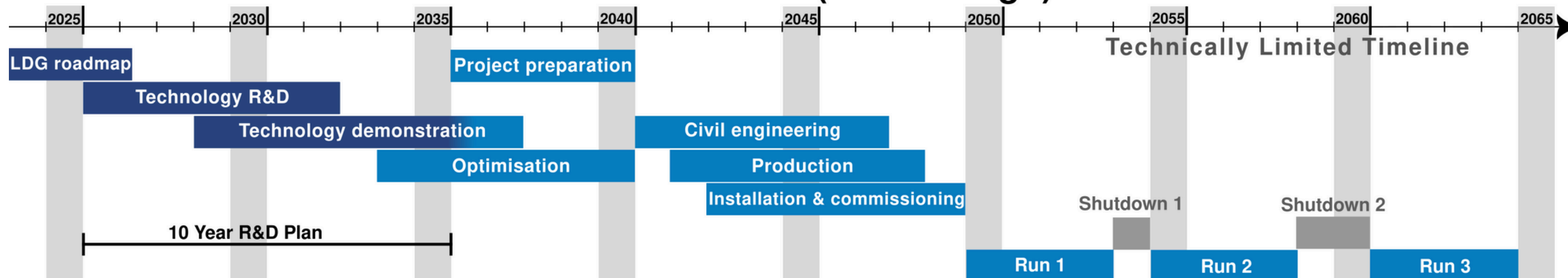
Muon Collider (Initial Stage)



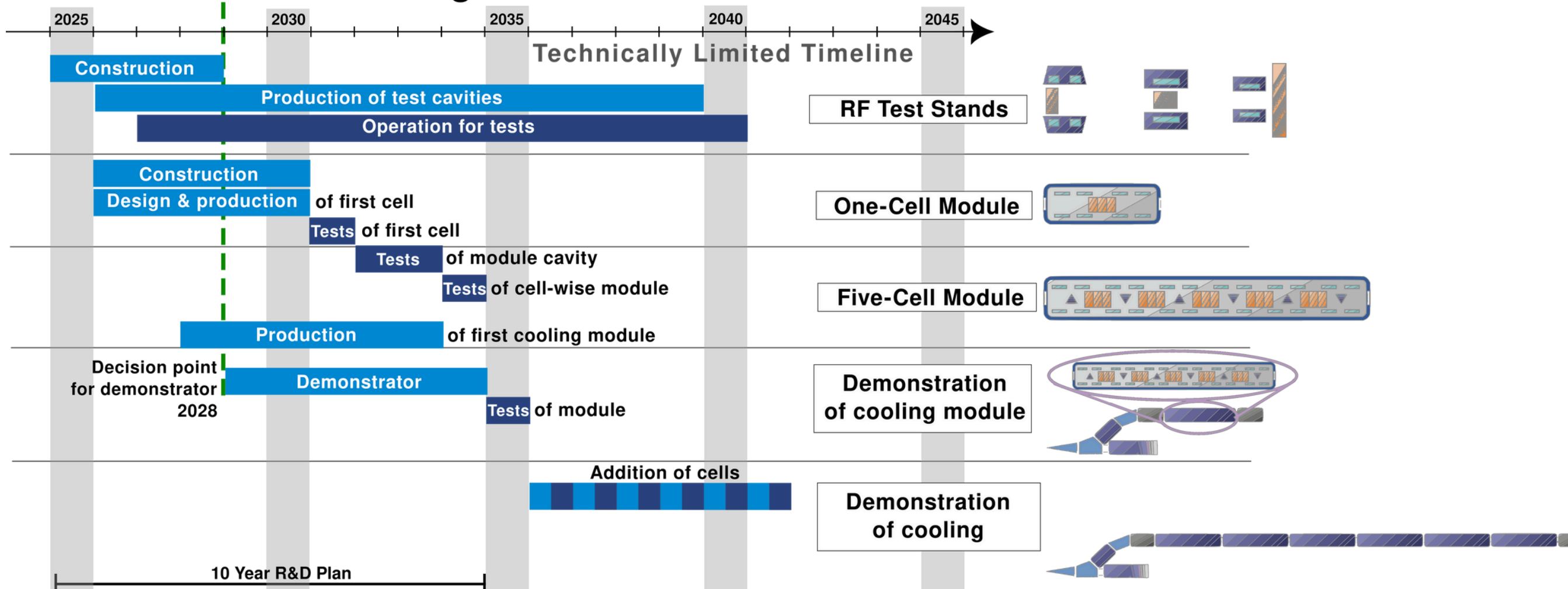
WHAT

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Muon Collider (Initial Stage)



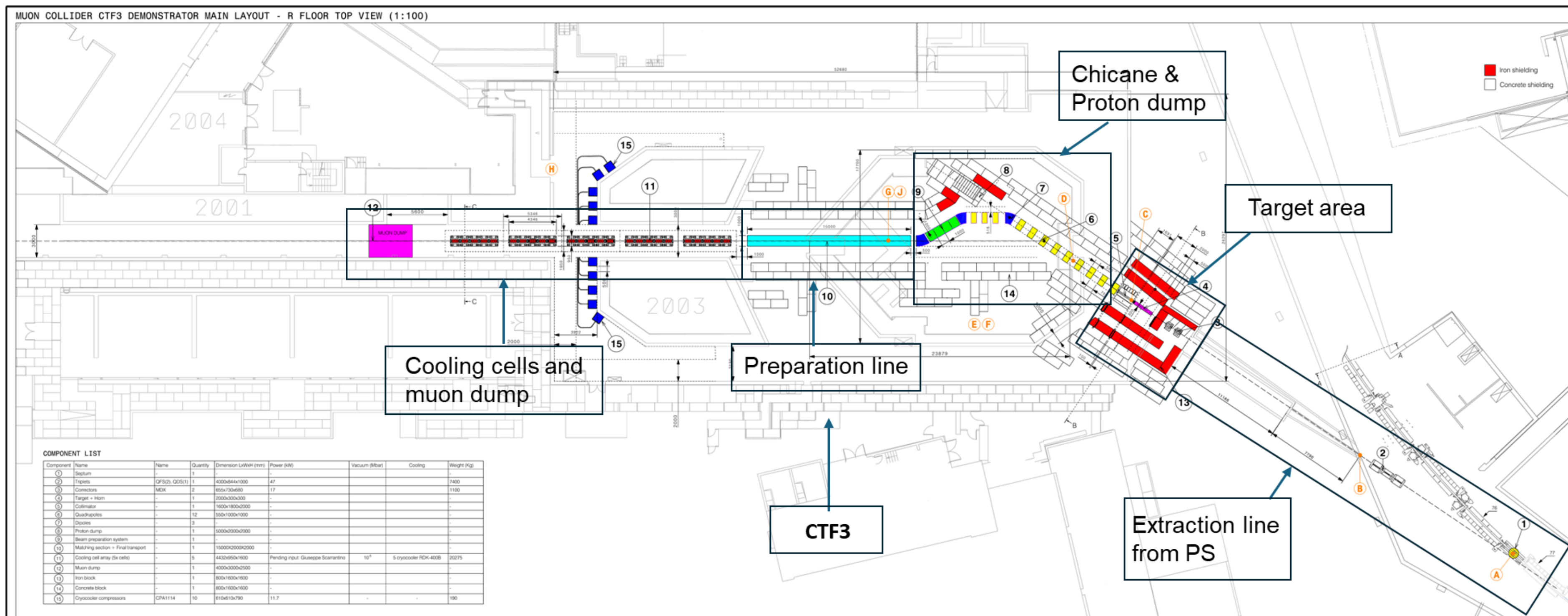
Muon Cooling Demonstrator



WHAT

do we need to do to collide muons?

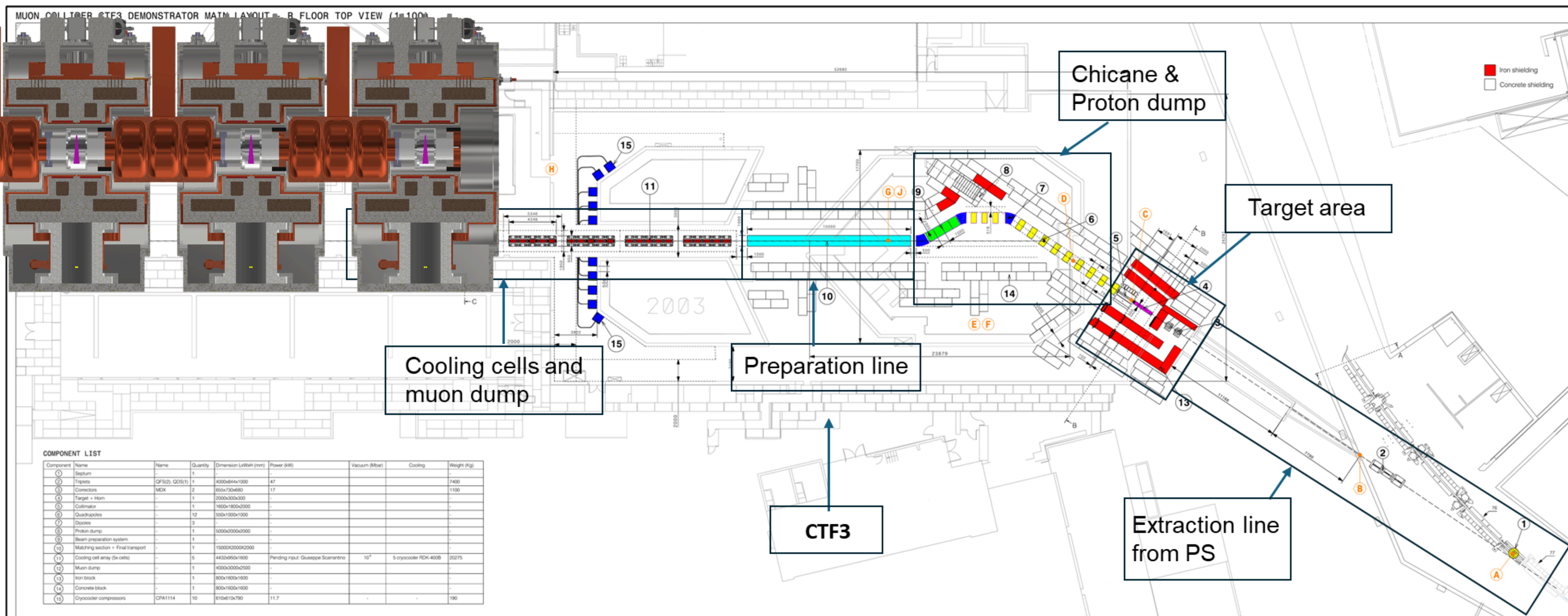
The Cooling Demonstrator



WHAT

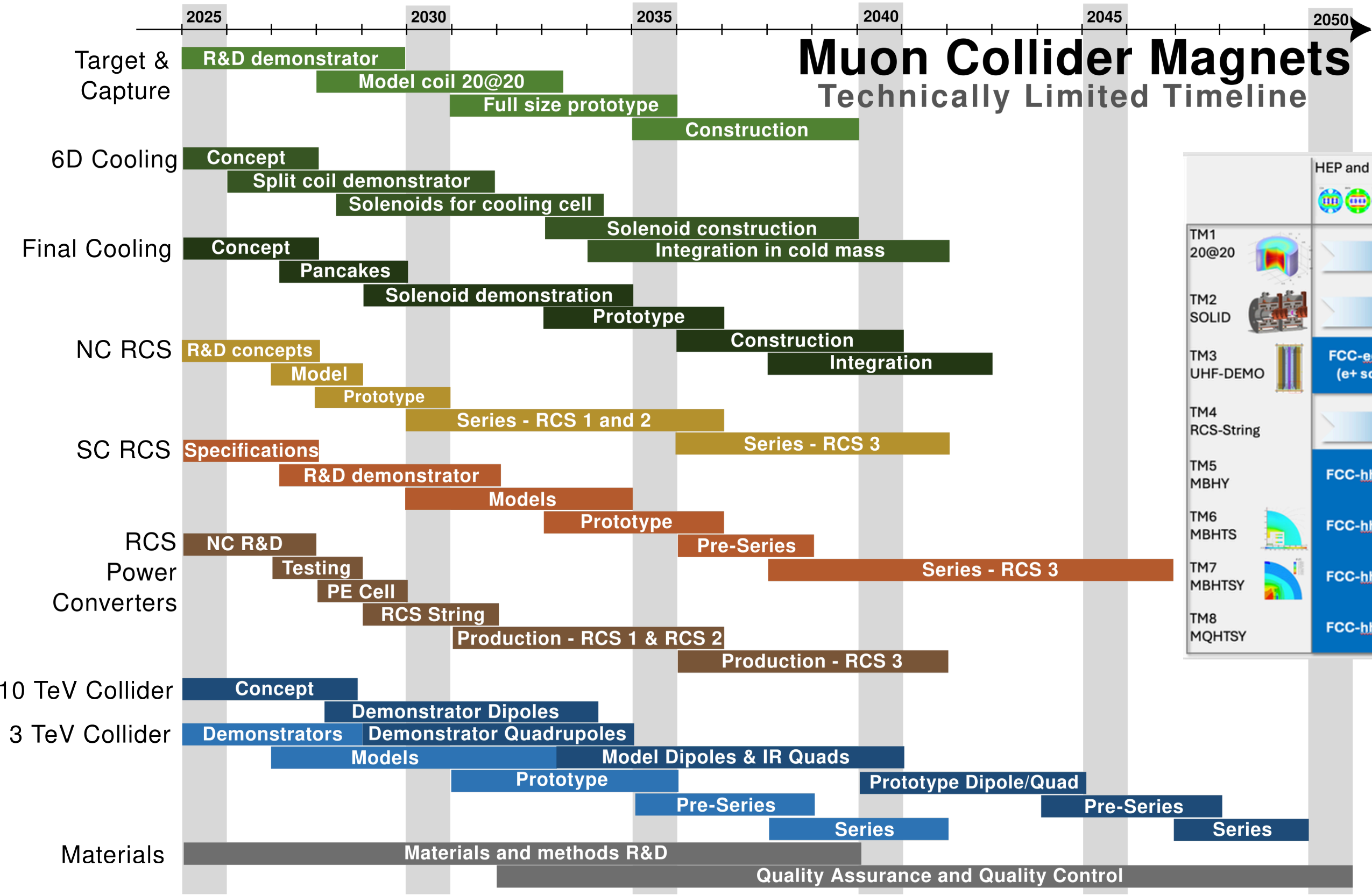
do we need to do to collide muons?

The Cooling Demonstrator



WHAT

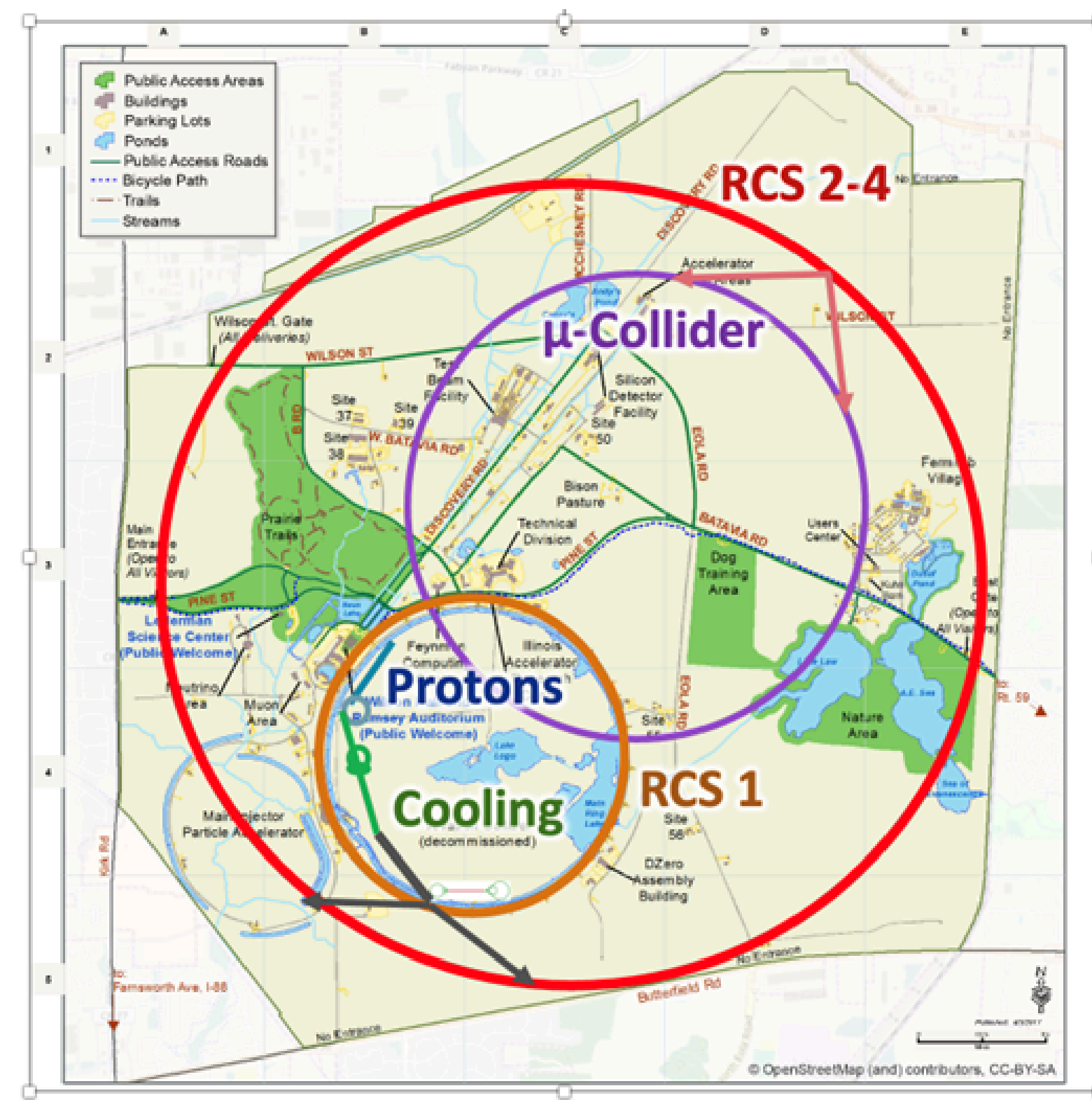
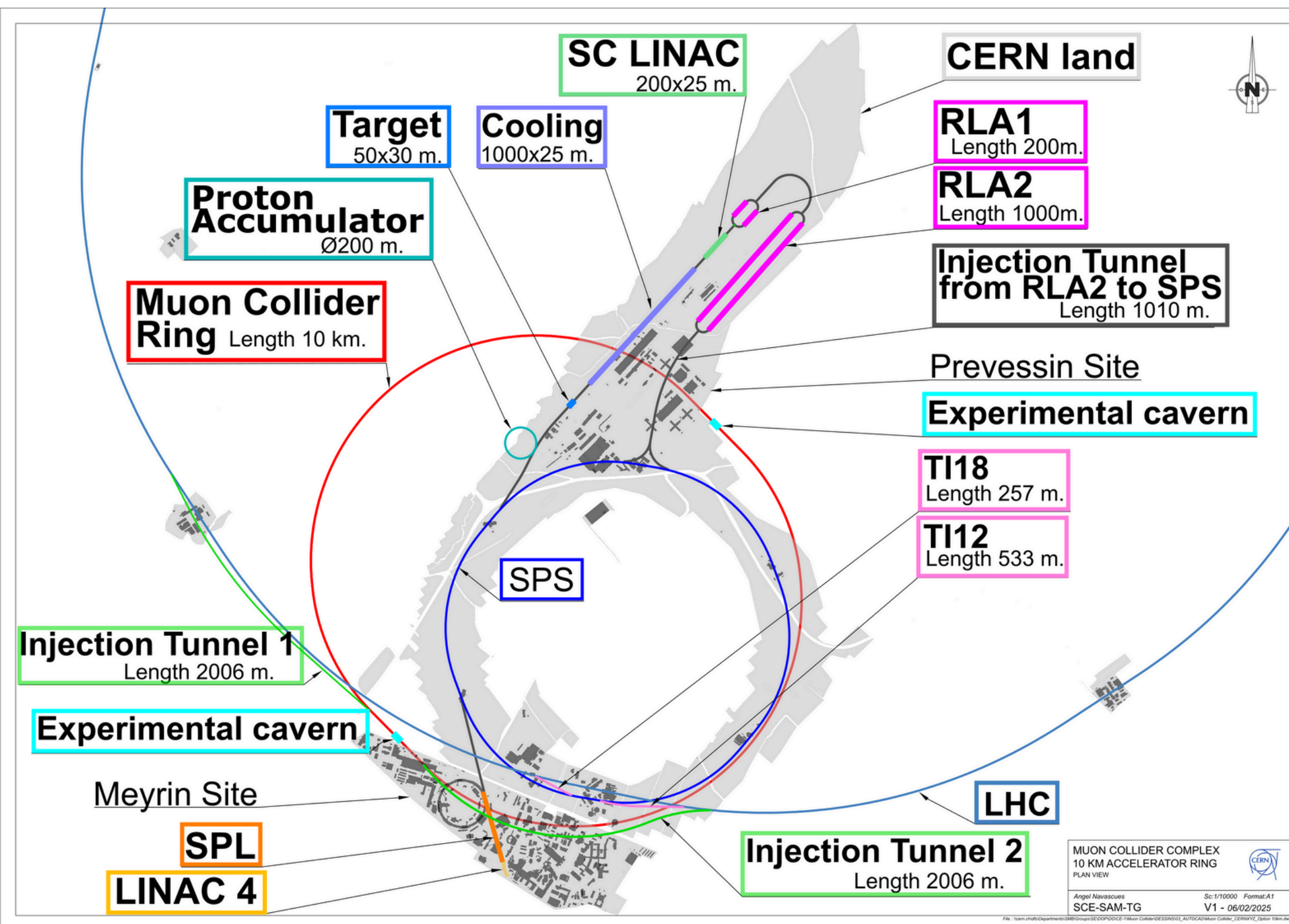
do we need to do to collide muons?



	HEP and NP	High-field science	NMR	MRI	Fusion	Motors/generators
TM1 20@20		High field, low consumption			High-field, large bore and large stored energy	
TM2 SOLID		High field, low consumption		High-field large bore, cryo-free technology		
TM3 UHF-DEMO		FCC-ee, CLIC (e+ source)	Ultra-high-field	Ultra-high-field		High-field, compact windings
TM4 RCS-String		High pulsed power and energy recovery			High pulsed power and energy recovery	
TM5 MBHY		FCC-hh, SppC				
TM6 MBHTS		FCC-hh, SppC				3D, compact pole winding
TM7 MBHTSY		FCC-hh, SppC				3D, compact pole winding
TM8 MQHTSY		FCC-hh, SppC				3D, compact pole winding

WHERE

might we collide muons?



WHO

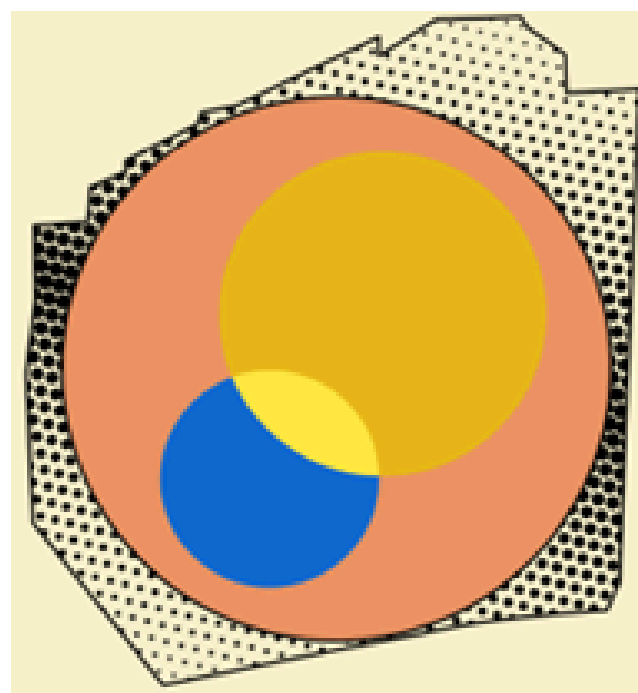
works on colliding muons?



- Formed by LDG after ESPPU 2022 R&D Roadmap
- 61 partner institutes, more joining regularly
- Follows from US Muon Accelerator Programme (2010-2017) 3 TeV study



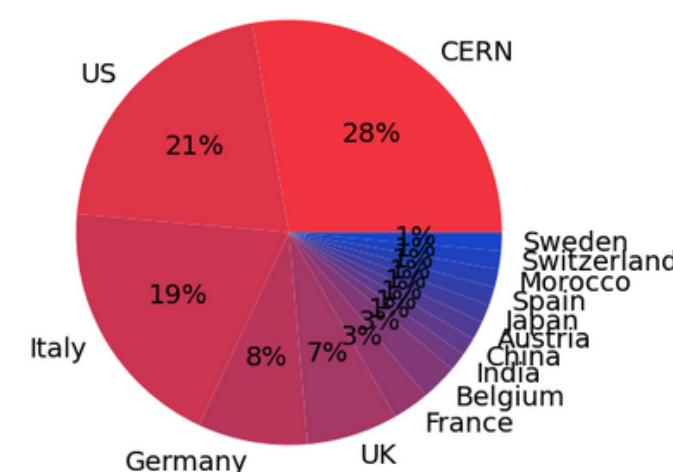
- EU Horizon project dedicated to 10 TeV design
- Began in 2023, resources until 2027
- Coordinates monthly milestones and deliverables, considering realistic performance goals



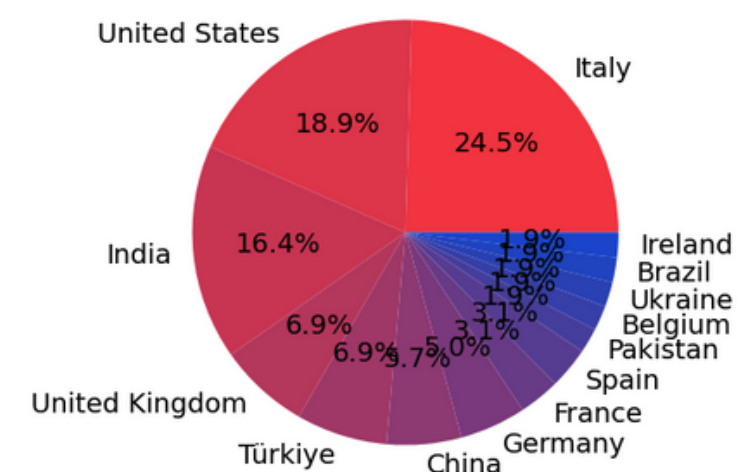
- USMCC initiated in 2024
- Following P5 *“Shoot For the Muon”*
- In the process of joining IMCC (CERN-DOE agreement)
- Strong collaboration, contribution to our ESPPU input
- Further support from National Academy of Sciences
- Grants obtained from labs and universities

Motivated Early Career community with dedicated events

IMCC Annual Meeting 2025
ECRs Country of Institute



ECR Online Event 2024
Nationalities with at least 2 attendees



IMCC Partners

IEIO	CERN	IT	INFN	FI	Tampere University		
FR	CEA-IRFU		INFN, Univ., Polit. Torino		<i>HIP, University of Helsinki</i>	CA	Université Laval
	CNRS-LNCMI		INFN, LASA, Univ. Milano	LAT	Riga Technical University	US	Iowa State University
	<i>Ecoles des Mines St-Etienne</i>		INFN, Univ. Padova	CH	PSI		University of Iowa
DE	DESY		INFN, Univ. Pavia		University of Geneva		Wisconsin-Madison
	Technical University of Darmstadt		INFN, Univ. Bologna		EPFL		<i>University of Pittsburgh</i>
	University of Rostock		INFN Trieste		HEIA-FR		Old Dominion
	KIT		INFN, Univ. Bari	BE	Univ. Louvain		Chicago University
UK	RAL		INFN, Univ. Roma 1	AU	HEPHY		Florida State University
	UK Research and Innovation		<i>ENEA</i>		TU Wien		RICE University
	University of Lancaster		INFN Frascati	ES	I3M		Tennessee University
	University of Southampton		INFN, Univ. Ferrara		<i>IFIC/CSIC</i>		<i>MIT Plasma science center</i>
	University of Strathclyde		INFN, Univ. Roma 3		ICMAB		Pittsburgh PAC
	University of Sussex		INFN Legnaro	China	<i>Sun Yat-sen University</i>		Yale
	Imperial College London		INFN, Univ. Milano Bicocca		IHEP		<i>Princeton</i>
	Royal Holloway		INFN Genova		Peking University		Stony Brook
	University of Huddersfield		INFN Laboratori del Sud		Inst. Of Mod. Physics, CAS		Stanford/SLAC
	University of Oxford		INFN Napoli		University of CAS		...
	University of Warwick	Mal	Univ. of Malta	KO	Kyungpook National University	DoE labs	FNAL
	University of Durham	EST	Tartu University		Yonsei University		LBNL
	University of Birmingham	PT	LIP		Seoul National University		JLAB
	<i>University of Cambridge</i>	SE	ESS	India	<i>CHEP</i>		BNL
NL	University of Twente		University of Uppsala	Signed MoC (61), <i>requested MoC</i> , contributor			
						Brazil	<i>CNPEM</i>

Conclusion



Physics:

Vector-Boson Fusion
Factory with strong physics
case at high energies,
especially for EW searches

Accelerator:

Many different systems
with no technological
showstoppers
identified

R&D:

10 year plan proposed
Includes magnets, RF
test stands and cooling
demonstrator

Community & Siting:

Growing collaboration at
both CERN and Fermilab.
Contributions from INFN,
STFC and universities.

**Increasing confidence that the muon collider is a unique, sustainable path to the future
of High Energy Physics.**

Need to ramp up momentum globally to achieve ambitious programme.

Synergies and knowledge transfer already opening up for magnets and power systems.

Enthusiastic and motivated international
community of:

- theorists
- experimentalists,
- detector designers
- beam optics physicists,
- magnet engineers
- RF engineers
- Civil engineers

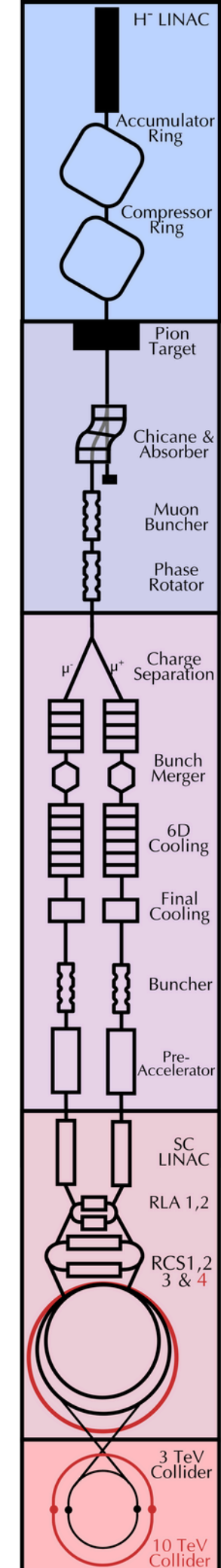
With equal mix of senior and early career



Many thanks to the collaboration for all the work

Our web page: <http://muoncollider.web.cern.ch>

If you want to join: muon.collider.secretariat@cern.ch



Thank you

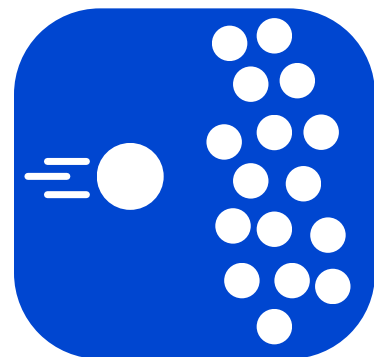


**Funded by
the European Union**

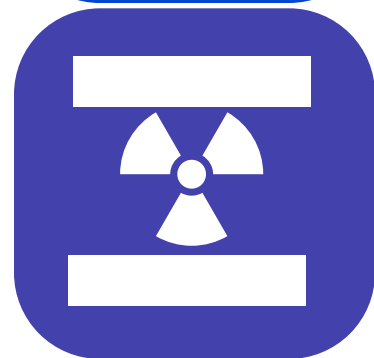
Funded by the European Union (EU). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the EU or European Research Executive Agency (REA). Neither the EU nor the REA can be held responsible for them.

End-To-End Simulation: Challenges

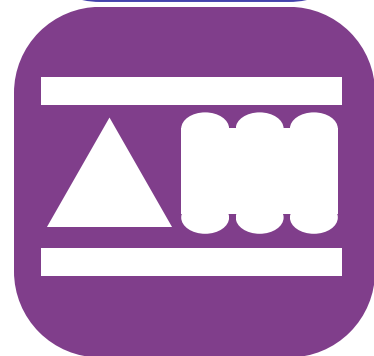
Simulation code wish-list includes...



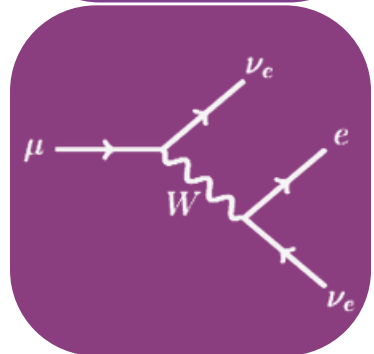
Particle interactions
with matter
Target, Cooling, MDI



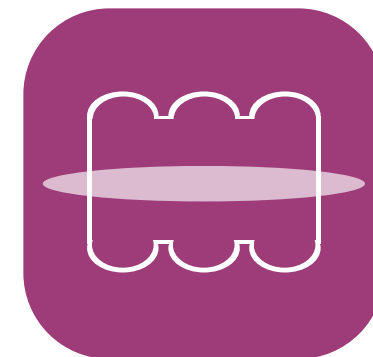
Radiation effects on
surrounding materials
Target, Collider



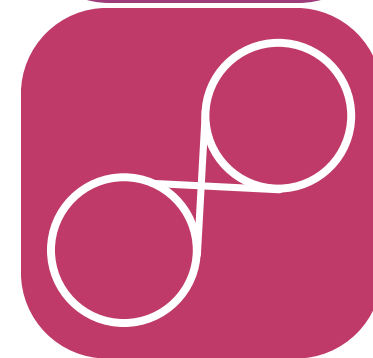
Overlapping elements
in high B_z fields
Target, Front-End, Cooling



Muon decay and
tracking secondaries
Everywhere



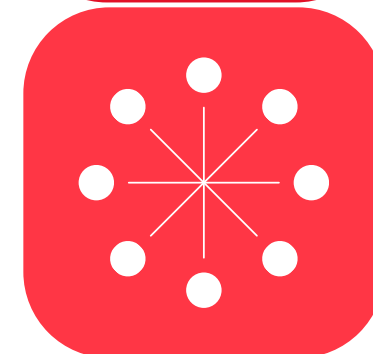
Low-energy linear
acceleration of a long beam
Cooling, Acceleration



Matching beam conditions
between synchrotrons
Accelerator, Collider, (Everywhere)



Non-linear effects
Collider



Collective effects including
space-charge, beam-beam
and wakefields
Everywhere